Gasification-based biomass fuel cycles : a decision and policy analysis.

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Gasification-based Biomass Fuel Cycles: An Economic and Environmental Analysis at the Regional Level

by

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Abstract

Heat and electricity generation from biomass integrated gasification combined cycle (BIG/CC) systems may represent an important future sustainable energy supply option at the regional level. BIG/CC systems are currently being demonstrated and their market penetration depends on their technical viability, and economic and environmental performance, in particular compared to conventional fossil-based fuel cycles.

This study provides an analysis of the economic and environmental performance of three region-specific BIG/CC case studies based on different biomass fuels: i) forestry residues in Sweden, ii) short rotation coppice and forestry residues in the UK, and iii) sugarcane residues in Brazil. The analysis includes a discussion of the regional context and biomass potential, a description of the fuel cycles and discussion of related technical issues and priority impacts, inventories of resource use, costs, emissions and employment, and a discussion of the external costs and benefits and sustainability of the fuel cycles. It provides key economic and environmental data in support of decision and policy-making and a discussion of issues related to market introduction. A comparison is provided with conventional reference systems (coal-based district heat and electricity in Sweden, coal and natural gas-based electricity in the UK, and bagasse combustion for industrial co-generation and natural gas-based electricity in Brazil).

The biomass fuels considered possess a large energy potential, and can currently be produced at reasonable cost and in an environmentally sound manner. Future commercial BIG/CC plants are expected to achieve high electrical efficiencies and significant cost reduction can be achieved compared to demonstration plants through economies of scale and replication. For co-generation applications, it is expected that the cost of energy could be competitive with that of conventional systems. For electricity only applications, BIG/CC electricity is likely to result in a cost premium, in particular compared to CCGT electricity.

BIG/CC systems offer significant reductions in emissions of regulated pollutants and CO_2 compared to conventional reference systems. Assessment of the externalities associated with regulated pollutants (NO_x, SO_2 and PM) shows that the use of BIG/CC systems results in significantly lower external costs. A comparison of the cost of energy based on social costs strengthens the position of BIG/CC systems, especially if the potential costs of climate change are considered. Reductions in emissions can be achieved at little or no additional private cost, and at a net social benefit, for co-generation applications and when substituting coal for electricity only generation. The cost of avoiding emissions, mainly CO_2, by substituting CCGT electricity is significantly higher. However, the avoidance costs for CO_2 are still within the range typical of damage costs cited in the literature.

BIG/CC systems hold promise as a sustainable energy supply option, based on biomass resource potential, projected cost reductions, and environmental and social benefits compared to conventional energy sources.

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[1] Now at HEW in Hamburg

[2] Now at University of Flensburg

To my mother, Rosalia,
and in memory of Prof. David Hall

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CHAPTER 1

INTRODUCTION

1 Introduction

The term "biomass energy" is generally used to describe energy obtained from solid, liquid or gaseous fuels derived from organic matter of plant or animal origin. Traditional sources of biomass consist of agricultural and forestry products and waste from animal husbandry. Industrial waste and specifically grown energy crops represent a more recent and increasing biomass resource. In some cases the concept is extended to municipal wastes which contain a large fraction of organic material.

Biomass has traditionally been used for domestic cooking and heating and such use is still widespread in particular in developing countries. Biomass use has declined sharply in domestic and industrial uses in developed countries during the industrialisation process due to the switching to fossil fuels (coal and oil). It is estimated that biomass accounts for about one seventh of world primary energy use and about one third of primary energy use in developing countries (Hall et al., 1999).

Biomass is often perceived as a low status fuel associated with poverty and low technological development, and its traditional use has in many cases contributed to an environmentally negative and unsustainable image of biomass energy. Indeed, biomass fuels the livelihoods of the world's poor, and is likely to continue doing so, but its role as a modern energy carrier is being increasingly recognised. Over the last two decades concerns over non-renewable resource availability, energy security and the environment have spurred scattered efforts for a larger scale use of biomass as a source of renewable, environmentally sound and competitive fuels, heat and electricity using modern conversion technologies. Recent energy projections indicate biomass as a major contributor to future energy supply (Hall and Scrase, 1998).

Biomass is often regarded as too inconvenient, expensive and resource (e.g. land, energy inputs) intensive as a modern energy carrier. However, many of the problems associated with biomass are largely misconceptions or amenable to solution. Adequately exploited and managed biomass resources can provide a renewable and sustainable source of energy which could ease pressure on the rate of consumption of non-renewable sources, in particular as world population grows and developing countries industrialise.

Biomass represents a large renewable energy source with potentially significant resource and economic advantages. Advances in the recovery of residues/wastes, the production of dedicated energy crops and the use of modern conversion technologies are fundamental to the competitiveness of biomass energy with conventional sources of energy. Also, biomass can provide considerable environmental benefits compared to fossil fuel use, in particular with regard to emission of noxious pollutants and greenhouse gases. The consideration of the environmental profiles of different energy options and of the social costs of fuel cycles in decision and policy making is necessary in the quest for more sustainable energy, and may contribute to more competitive biomass energy compared to its conventional counterparts. The worldwide trend of the energy sector away from vertically integrated utilities and strongly centralised power generation to a more competitive and decentralised power supply market could provide great opportunities for biomass energy (Patterson, 1999). The social dimension of biomass energy is also of importance as its development may in many cases be accompanied by socio-economic benefits (e.g. rural development). Biomass energy appears then to possess a significant potential to contribute toward a more sustainable energy path.

2 Biomass use and potential

The share of primary energy provided by biomass in industrialised countries is small and is estimated at about 3% (Hall and House, 1995). However, the use of biomass energy varies considerably depending on factors such as resource availability and government policies. Biomass provides about 4% of primary energy in the US, 14% in Austria, 18% in Sweden and 20% in Finland (Hall et al., 1999).

The picture is different in developing countries where biomass is estimated to provide about one third of primary energy consumption. The contribution of biomass is estimated to vary from over 90% in less developed African countries such as Uganda, and Tanzania, to about 45% in India, 28% in China and Brazil and 10-15% in Mexico and South Africa (Hall et al., 1999).

Most biomass use in developing countries is of the traditional type, mainly for domestic heating and cooking. Part of the biomass is used in industries, mainly in the food processing industry and in some other industries such as brick manufacture. Traditional biomass use is inefficient and often a source of environmental concern, in particular with regard to the health of those exposed to combustion emissions in households. Conversion efficiencies are low, typically 10 - 15% in domestic applications and 15 - 20% in industrial applications.

Traditional use of biomass is not likely to decline in the near future as it provides a means of subsistence for the world poor. Hence, the importance of programmes aimed at improved traditional uses and at the management of biomass resources where traditional use of biomass is made.

Biomass is used for domestic heating in industrialised countries. Efficiencies are higher compared to developing countries, in particular where modern domestic boilers/stoves are used and in the case of district heating schemes, with efficiencies generally above 60%. Part of the biomass in industrialised countries is used for electricity generation - about 20% of biomass use in the European Union. Though, average generating efficiencies are low, typically 20 - 25%. Overall heat and electricity generating efficiencies in modern combined heat and power plants can exceed 80%.

Current commercial and non-commercial biomass use for energy represents about 14% of the world primary energy, which corresponds to about 55 EJ (Hall et al., 1999). There is a great potential for both an improved and increased use of biomass for energy worldwide.

The worldwide biomass potential is large. There is a large unused potential of plant (woody and herbaceous) and animal residues and wastes. Additional to this, there is a significant potential for biomass from the afforestation of deforested and degraded lands and from energy crop plantations on agricultural land.

Biomass potentials are difficult to estimate precisely. Bauen and Kaltschmitt (1999a) estimate the solid biomass potential from woody residues from forestry and agriculture and herbaceous residues from agriculture in the European Union at about 4.2 EJ compared to the overall current biomass use of about 1.8 EJ. For the US, the estimated recoverable biomass potential is about 15 EJ, of which woody residues from forestry and agriculture and herbaceous residues from agriculture represent about 12 EJ, compared to an overall current consumption of biomass energy of about 2.8 EJ (Klass, 1995; Overend and Costello, 1998). Biomass potentials for Africa, Asia and Latin America & the Caribbean have been estimated at about 11 EJ, 20 EJ and 13 EJ, respectively (Bauen and Kaltschmitt, 1999b). Higher potential estimates could be envisaged if energy crops are considered. Thus, for the European Union alone, these could contribute about 2.6 EJ.

A number of global energy scenarios published in recent years indicate that biomass is likely to play a major role in future energy supply. The biomass energy contribution estimates range between about 60 and 145 EJ in 2025 and between about 130 and 320 EJ in 2010, depending on assumptions on the evolution of primary energy demand and environmental constraints (i.e. limits on CO_2 emissions) (Hall et al., 1999).

3 Biomass fuel cycles

3.1 Biomass sources and types

Biomass is available in different forms and there are many ways in which it can be classified. For example, it can be classified according to its source (i.e. animal or plant) or according to its phase (i.e. solid, liquid or gaseous). Generally, biomass energy can be derived from the following sources: forests and energy crop plantations; residues from primary biomass production; and by-products and wastes from a variety of processes. In the case of plant biomass, distinction is often made between woody and non-woody biomass.

Forests, woodlands, short rotation forestry plantations and other trees outside forests or woodlands are a source of wood fuel. Energy crop plantations include species such as willow, poplar, eucalyptus, sugarcane, miscanthus, reed canary grass, cynara, sorghum, energy grain, hemp, oilseed rape, sunflowers and sugar beet. Residues from primary plant biomass production include residues from food and industrial crop production (e.g. cereals, sugarcane, tea, coffee, rubber trees, oil and coconut palms) and residues from forestry activities (e.g. residues from stem wood production). By-products and waste may originate from a variety of sources and include sawmill waste, manure, sewage sludge, abattoir waste and municipal solid waste. By-products are distinguished from waste in that they possess a commercial value other than for energy, however the distinction between the two categories may not always be evident.

3.2 Biomass conversion technologies for modern biomass use

Biomass is suitable for a wide range of energy uses. It can be burned directly to generate heat and electricity or converted to intermediate solid, liquid or gaseous fuels.

3.2.1 Biomass direct combustion

Biomass can be burned in small-scale modern boilers for heating purposes or in larger boilers for the generation of electricity or combined heat and power (CHP) (see for example Obernberger, 1998; van den Broek et al., 1996). Most electricity generation is based on the Rankine (steam turbine) cycle, where biomass is burned in a boiler to produce pressurised steam which is then expanded in a steam turbine to drive an electricity generator.

Biomass combustion plants are classified according to the boiler technology. The technology used influences the pre-treatment of the biomass fuel and flue gas cleaning activities. The most common boiler types are: pile burners, stoker fired boilers, suspension fired boilers and fluidised bed boilers. In the case of the pile burner, piles of biomass are dumped in a furnace and burned with the aid of combustion air supplied from below and above the pile. In stoker fired boilers a grate is used to control biomass distribution during combustion. There are three types of stoker fired boilers: the sloping grate boiler, the travelling grate boiler and the vibrating grate boiler. The sloping grate allows the biomass fuel to burn as it slides down the slope, the travelling grate allows the biomass to burn as it is transported across the boiler, and the vibrating grate allows the fuel to be spread out evenly as it is burned. In suspension fired boilers the biomass fuel is burned as it falls across the boiler, in a similar way to pulverised coal technology. In fluidised bed boilers the oxidising agent (e.g. air) is blown into the boiler from below to create a layer in which the biomass particles are mixed and combusted through interaction with an inert material (e.g. sand). There are two principal types of fluidised bed boilers: the bubbling bed boiler and the circulating fluidised bed boiler.

Most European examples of biomass fuelled stoker fired, suspension and fluidised bed boilers are situated in Austria, the Netherlands, Denmark, Sweden and Finland.

Co-combustion of biomass and coal may be a promising option in existing or new coal plants. Pulverised fuel (PF) and (circulating) fluidised bed ((C)FB) conversion technologies appear as promising candidates for co-combustion. European activities have ranged from laboratory to full-scale demonstration in power plants, with the Netherlands, Denmark, Sweden and Germany being amongst the most active players. Co-combustion of woody biomass appears most viable at present. The use of other biomass sources such as annual energy crops, crop residues and other biomass wastes require further development and demonstration. Problems such as slagging, fouling and high temperature corrosion need more careful consideration when utilising non-woody biomass. Extensive experience exists with co-firing woody biomass in Sweden. The greatest experience to date with non-woody biomass has been gained by the Danish Greena CFB plant co-firing coal and straw. Generation costs, in the absence of incentives, are likely in most cases to be higher compared to the use of coal alone. However, the benefits in terms of emissions and resource use are likely to be important. As an alternative to co-firing, separate biomass boilers could be added to coal plants to generate additional steam. For certain biofuels, such as straw, steam temperatures may need to be lower than the steam temperature generated in the fossil-fuelled boilers because of corrosion problems.

3.2.2 Biomass thermochemical conversion

Biomass gasification

Biomass gasification converts biomass to a low to medium calorific value (4-20 MJ/Nm^3) gaseous fuel. The fuel can be used to generate heat and electricity by direct firing in engines, turbines and boilers (see for example Kaltschmitt and Bridgwater, 1997; Kaltschmitt et al., 1998). Alternatively, the product gas can be reformed to produce fuels such as methanol and hydrogen, which could then be used in fuel cells for example.

Gasifiers of the fixed bed type are best suited for small-scale applications. There are three types of fixed bed gasifier designs: up-draft (or counter-current), down-draft and cross-flow. Up-draft gasifiers are most popular for thermal capacities up to $10MW_{th}$. The high tar content of the product gas makes them less suitable for small-scale electrical power applications compared to the down-draft design which produces a cleaner gas. However, down-draft gasifiers are limited in thermal capacity to about $4MW_{th}$ and this may be the reason why recent attention has focused on the up-draft design. Extensive experience exists with wood and peat up-draft gasifiers for heat production in Finland (e.g. the Bioneer system). More recently systems are being developed to operate with straw, refuse derived fuel (RDF) and sewage sludge.

Recent gasification activities in the EU have focused on circulating fluidised bed systems. Circulating fluidised bed gasifiers coupled to engines, gas and steam turbine cycles are an interesting option for CHP or electricity generation at medium to large scale. High and low (quasi-atmospheric) pressure systems are the demonstration stage. A low-pressure system will be slightly less efficient than the high-pressure system. However, greater uncertainty surrounds the reliability of certain components of the high-pressure systems (e.g. hot gas clean-up system). The only demonstration plant commissioned to date is the HP-BIG/CC plant in Värnamo, Sweden.

Gasification based co-utilisation of biomass and fossil fuel is being investigated. The following options are being examined: use of biomass with coal in a large pressurised coal gasification plant; separate gasification of biomass and co-combustion of fuel gas with coal in pulverised fuel boilers or with natural gas in gas boilers or turbines. Co-gasification of biomass and coal in pressurised entrained flow gasifiers appears to be problematic, in particular in relation to biomass fuel preparation and feeding. The gasification of non-woody biomass fuels presents additional difficulties because of the low sintering temperature. Most co-utilisation activities have so far focused on woody biomass, including demolition wood. The use of sewage sludge as a part feedstock with hard coal is also being investigated.

Biomass pyrolysis

Biomass pyrolysis produces a liquid fuel which can be transported and stored and allows for de-coupling of the fuel production and energy generation stages. The fuel can be used to generate heat and electricity by combustion in engines, turbines and boilers (see for example Bridgwater, 1998; Kaltschmitt and Bridgwater, 1997). Products other than liquid fuels can be obtained from pyrolysis, such as charcoal and fuel gas. Pyrolysis technology is, however, at an earlier stage of development than combustion and gasification. There are different types of pyrolysis reactors, like the rotating cone reactor, the (circulating) fluidised bed reactor and the ablative reactor. Each will have different biomass feed specifications and different liquid fuel yields. Feed size ranges from about a fifth of a millimetre to a few centimetres and liquid fuel yields are generally between 65% and 75% based on dry biomass input. Liquid fuels from biomass pyrolysis are being tested in boilers, engines and turbines.

3.2.3 Biological conversion

Anaerobic digestion

Anaerobic digestion is a biological process consisting of a sequence of hydrolysis, fermentation, acidogenesis and methanogenesis leading to a medium calorific value gas (c. 20 MJ/Nm^3). The gas consists mainly of methane and carbon dioxide and contains various trace elements. Numerous companies worldwide have commercialised different reactor designs. Farm-based facilities are probably the most common, in particular in countries like China and India, and interest is growing for the use of anaerobic digestion in sewage treatment facilities, for the processing of the organic fraction of municipal solid waste (MSW) and to treat industrial organic waste. In Europe the country with most experience is Denmark. There are 18 large centralised facilities in operation which co-digest manure, clean organic industrial wastes and source-separated MSW. The solid and liquid residues from the anaerobic digestion process can be used as compost and fertilisers.

Ethanol production

The bioethanol production process depends on the type of biomass considered. Sugar, extracted from crops such as sugarcane, can be fermented into ethanol by various organisms including yeast and bacteria. Starch from crops such as corn needs first to be broken down to simple glucose sugars by acids or enzymes, and the same applies to cellulosic biomass. Hemicellulose, a principal component of cellulosic biomass together with cellulose, is broken down into a series of different sugars which are more difficult to ferment than the simple glucose resulting from the hydrolysis of cellulose. However, progress is being made in the use of micro-organisms to convert sugars derived from hemicellulose into ethanol. In all cases the ethanol produced contains significant quantities of water and distillation is used to reduce the water content. The largest ethanol production programme in the world is the ethanol from sugarcane (PROALCOOL) programme in Brazil. France is the largest ethanol producer in Europe, using sugar beet.

3.2.4 Physical-chemical conversion

The physical-chemical conversion route applies to biomass from which vegetable oil can be obtained and consists of pressing and extracting oil from the biomass. Vegetable oils can be used in special engines or in diesel engines after an esterification step leading to the production of oil methyl ester. Biofuel from oilseed rape is produced in several European countries, the largest production being in Germany.

3.3 Biomass fuel cycles

It is difficult to define a typical biomass fuel cycle because of the diversity of biomass sources and types, conversion processes and biomass energy end-uses. Figure 1 provides a schematic representation of different biomass conversion routes for the production of heat and electricity. In general, solid biomass for heat and electricity fuel cycles will consist of biomass production, transportation and conversion stages. However, while energy crops involve important production and transportation stages, these stages may not be required in the case of process residues (e.g. sugarcane bagasse used for energy generation at the mill site). Energy crops will require agriculture and forestry type activities which could be intensive with respect to agrochemical inputs, machinery use and labour. The transport stage may also have important economic and environmental implications because of the low energy density of biomass. The disposal of wastes from biomass energy systems (e.g. ash, residues from anaerobic digestion) is generally not a problem and in many cases the waste will be of some value (e.g. as a fertiliser).

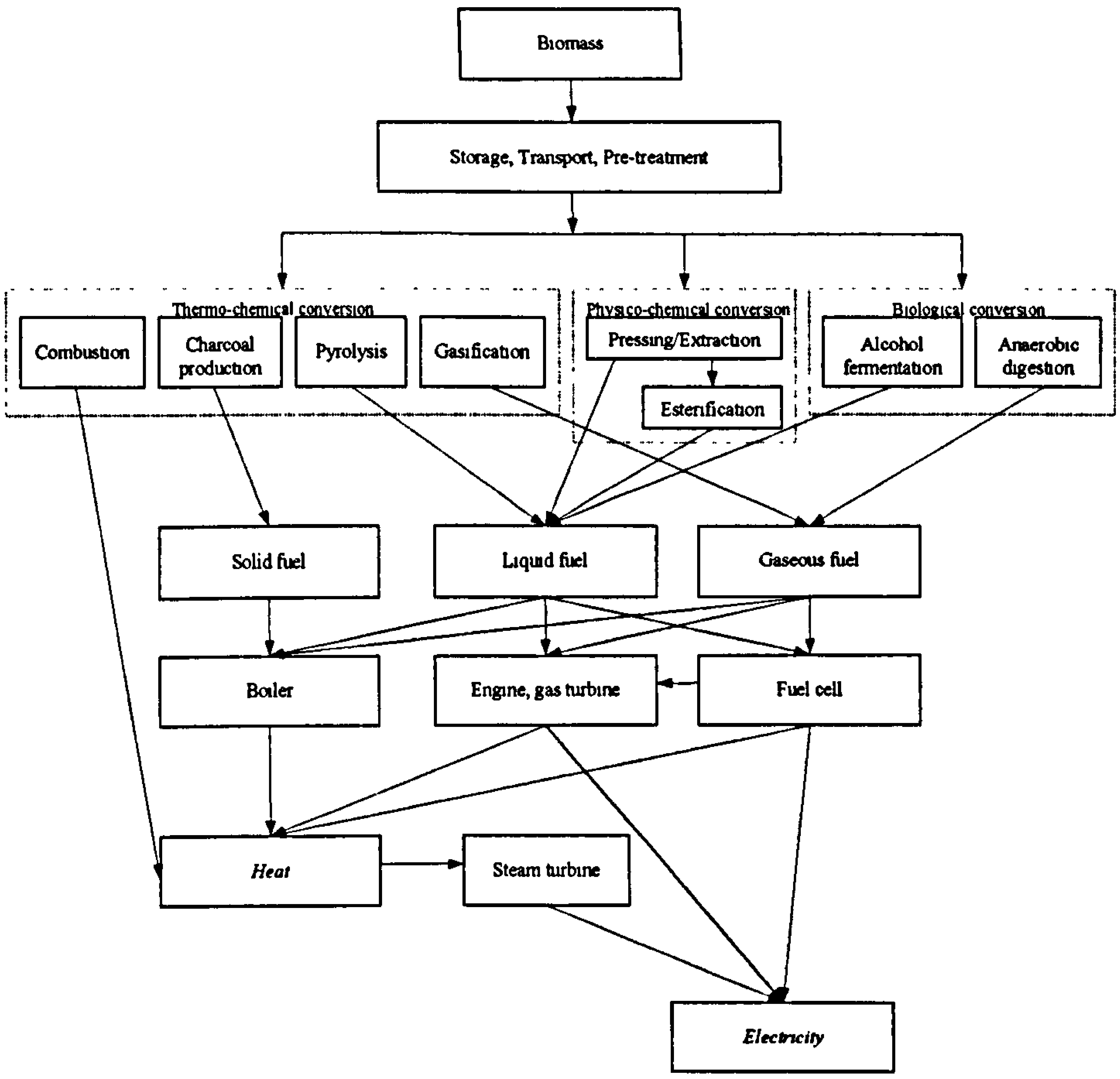

Figure 1: Biomass conversion routes

4 Issues in modern biomass use

There are a series of issues related to biomass which need to be addressed (Hall and Scrase, 1998).

Biomass is considered an inconvenient fuel. In fact, it is generally a bulky fuel of variable quality, whose conversion to useful energy may require an important pre-treatment or upgrading step. However, significant advances have been made in the handling of biomass fuels and in their pre-treatment and upgrading, and commercial technologies are available. Initial steps are also being taken towards standards for biomass fuels.

Biomass energy is often believed to require excessive land areas. In particular, concern is often expressed that significant reliance in biomass energy can be achieved only at the expense of food production. However, it is very unlikely that biomass will one day satisfy the totality of world energy demand, and even if it were so different sources (see for example Hall and Scrase, 1998) claim that it would be possible through a mix of energy crops and residues while still producing enough food. Fuel versus food arguments aside, it appears that significant quantities of biomass energy could be derived from residues, by-products and waste. Also, in the case of energy crops for electricity generation, land requirements need not necessarily be a concern. If an electrical efficiency of 40% and a biomass yield of 15 odt/ha/yr are assumed, a 50 MW electrical capacity plant would require about 10% of the land within a 20 km radius from the plant or about 1.7% of the land within a 50 km radius. The specific land requirement for the plant would be about 250 ha/MW_e.

The energy balance of biomass fuel cycles is sometimes questioned. However, several studies have shown that the energy balance for heat and electricity from biomass is generally very favourable (see for example Kaltschmitt at al., 1997). The energy balance issue may be more controversial in the case of liquid fuels from biomass (e.g. rape seed oil and ethanol from sugar beet – CEC, 1998b), though in cases such as ethanol production from sugarcane the energy balance appears again to be very favourable (Macedo, 1998).

Biomass is regarded as an expensive fuel. Again, it is difficult to generalise. While biomass from energy crops may indeed incur relatively high costs, certain biomass forms (i.e. certain residues, by-products or wastes) may be available at little or no cost, or even at a negative cost in the case where a tipping fee may apply to some waste products. In Sweden, wood fuel is used commercially on a relatively large scale and its price is about $4 per GJ (Hillring, 1997), which is high relative to that of fossil fuels (e.g. the world market price for coal is about $1.8 per GJ). However, it needs to be considered that fossil fuels often benefit from high subsidy levels and their costs do not account for any externalities, environmental damage costs in particular. It is estimated that global fossil and nuclear energy subsidies are about $300 billion per year (see for example Bauen, 1996; Myers, 1998 and Roodman, 1998). Another reason for the higher cost of biomass energy compared to conventional alternatives is the relatively early stage of commercialisation of many biomass technologies.

The question is also raised as to how environmentally benign biomass energy is (see for example Zoethout, 1999). The environmental impacts of biomass energy will depend on the type of biomass considered. In the case of energy crops, the impacts on the environment of the activities involved in the production and transport of the biomass may be of concern. Good practice can considerably limit any negative impacts and guidelines have been extensively published (see for example ETSU, 1996; ARBRE, 1996b and Ledin and Alriksson, 1992). Generally, biomass provides a relatively clean fuel with very low sulphur content and very low levels of trace elements of concern such as heavy metals. Modern biomass conversion technologies for heat and electricity generation can produce very low levels of NO_x and particulate emissions. Biomass energy systems may present significant environmental benefits with regard to so-called regulated pollutants (NO_x, SO_2, PM) in particular compared to conventional fossil fuel based alternatives. The environment may also benefit from energy plantations in terms of, for example, improved soil quality and biodiversity. Biomass finally possesses a clear environmental advantage as a CO_2-neutral fuel.

5 Decision and policy making framework

The current decision and policy making framework and its evolution is of key importance to the market introduction of biomass energy. Decisions by players in the energy sector will take into consideration mainly the competitiveness of alternative energy sources. The regulation and policy measures in place (e.g. energy market regulation and environmental policies) will strongly affect the competitiveness of different energy options. An increasing energy demand worldwide, pressing environmental issues and evolving energy market structures are all likely to lead to a decision and policy making framework which will favour the introduction of environmentally sound and competitive renewable energy sources.

5.1 World energy situation

World energy consumption is large and increasing. Primary energy consumption in 1996 was estimated at 9,376 Mtoe (392.5 EJ) (*Figure 2*). Annual per capita energy consumption is about 4.60 Mtoe for OECD countries, and 0.98 Mtoe for the non-OECD countries. CO_2 emissions for 1996 are estimated at 22.7 Gt. Annual per capita CO_2 emissions are about 11.09 t for OECD countries, and 2.32 t for the non-OECD countries. Primary energy demand is increasing and estimated by IEA (1999a) to reach 11,500 Mtoe in 2010 and 13,700 Mtoe in 2020, corresponding to an average annual increase of 2% until 2020. Electricity consumption, estimated at 13,652 TWh in 1996, is increasing at a faster rate. The increasing demand and pressure on conventional power sources is likely to lead to an increased contribution of renewable energy sources, including biomass, to future energy supply.

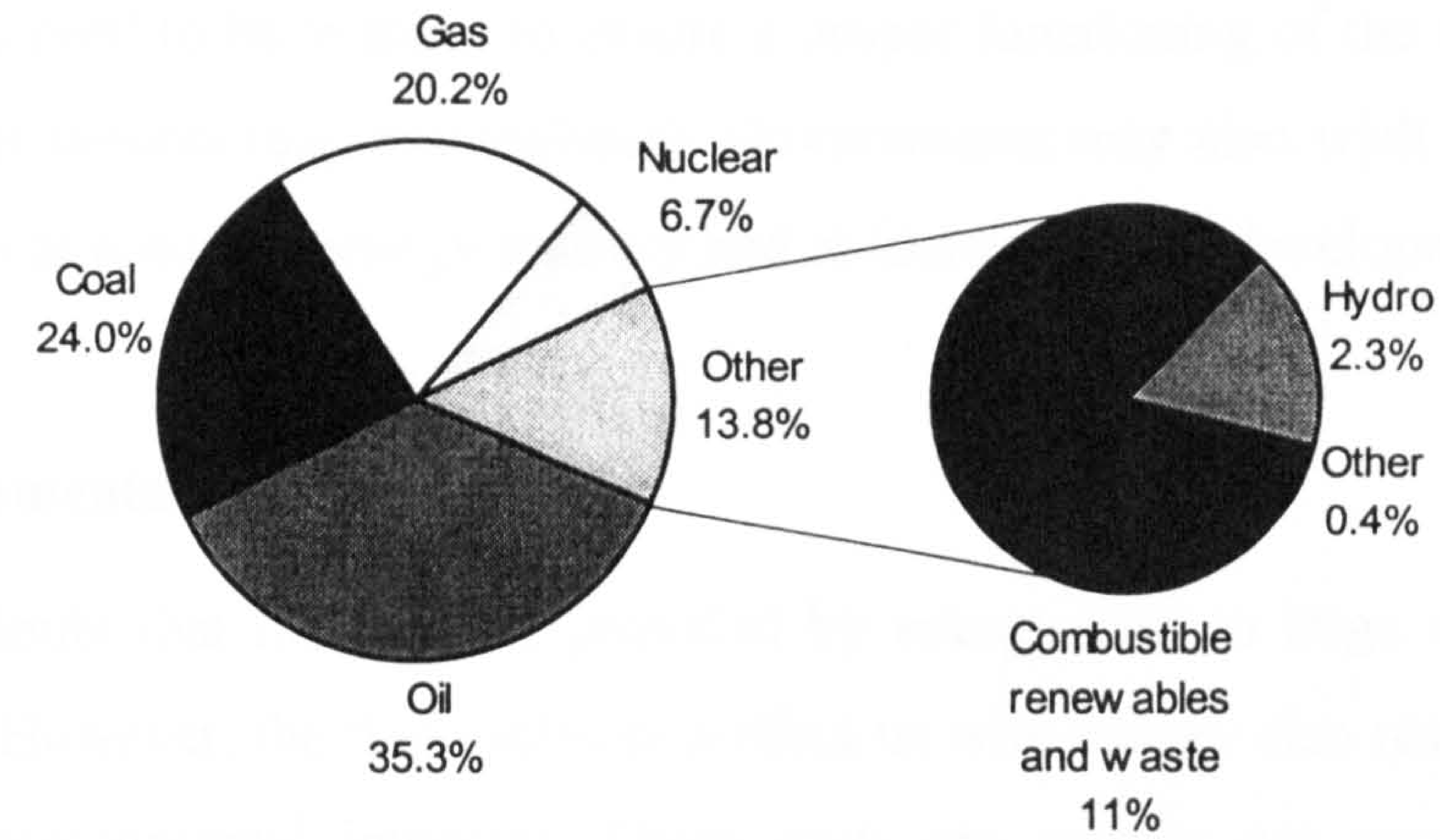

Figure 2: World energy consumption (392.5 EJ) (Source: IEA, 1999a)

5.2 Market structure

In most countries energy is supplied by vertically integrated state owned utilities. This market structure, which has favoured large-scale centralised electricity generation, has been increasingly challenged over the last decade (Patterson, 1999). The present trend is towards a liberalised market in which energy generation, distribution and supply are disentangled and provided by private firms.

Current investments in energy generation by utilities and industries are principally based on private cost-benefit analysis, inclusive of taxes, incentives and additional costs imposed by command-and-control measures. Utilities will take into consideration the capital intensity and rate of return of the investment, the supply obligations they have to fulfil (e.g. reliability) and the policy constraints in place, such as least cost planning and demand side management (as consumers are interested in the services energy provides and not in energy itself as a commodity). Industry wishing to generate heat and/or electricity on site will analyse its own demand, fuel availability, in particular in the case of biomass, and capital intensity and rate of return of the investment. Industry and independent power producers (IPP) wishing to sell electricity to the grid will consider the conditions governing access to the grid and at the price at which they can sell the electricity.

A liberalised market is likely to favour smaller scale, less capital intensive projects, as well as the entry of new players in the market. However, sufficient regulatory and policy measures need to be in place to ensure a proper functioning of the market and to deal with market failures (e.g. externalities). Governments may also wish to implement policies that aim at ensuring energy security and at fostering rural development.

5.3 Environmental considerations

There is little doubt that the services provided by energy lead to large economic and social benefits. However, the fuel cycles providing us with energy also result in costs to society (e.g. environmental impacts). These costs are usually not accounted for in private sector decisions regarding the fuel cycles, that is they result in externalities. The true cost of energy should ideally account for these externalities. The establishment of a level playing field, which takes into consideration the externalities of energy systems, as well as the elimination of other subsidies which create negative distortions, is fundamental for the competitiveness of clean and renewable energy systems.

6 The future of biomass

There are a series of factors which could lead to a renewed perception and an enhanced use of biomass energy:

- an increasing energy demand worldwide in association with an increased awareness of the energy potential of biomass;
- evolving regulatory, institutional and policy frameworks driven by market liberalisation, as well as by environmental and social considerations;
- improvements and cost reductions in biomass production, transport and conversion;
- possible economic, environmental and social benefits of biomass use compared to alternative energy sources, at the local, regional and global scale.

It is of key importance to demonstrate that modern biomass energy can contribute significantly to future energy supply, compete with conventional fuel cycles on economic grounds, provide environmental advantages compared to conventional fuel cycles, and be accompanied by a series of other economic, environmental and social benefits. These are all requirements that will ensure that biomass energy has a role to play in future sustainable energy supply.

Gasification based biomass fuel cycles provide a potential route for clean and efficient energy generation which is worth assessing and discussing with regard to decision and policy issues.

7 The thesis

The thesis argued in the present work is that gasification-based biomass fuel cycles for heat and electricity generation could represent an important sustainable energy source at the regional level.

7.1 Rationale

The rationale for the thesis rests on the following arguments:

- biomass is a widespread, diverse and renewable resource;
- renewably grown biomass is a carbon dioxide-neutral fuel;
- modern conversion technologies allow for an efficient and clean use of biomass;
- biomass energy may present numerous environmental and socio-economic advantages over conventional energy sources;
- changing decision and policy making frameworks may offer greater opportunities for biomass energy.

The global biomass energy potential is estimated to be large, and predictions by institutions such as the Intergovernmental Panel on Climate Change, the International Energy Agency, the World Energy Council and Shell International indicate that renewables, biomass in particular, will play a major role in future energy supply (Hall et al., 1999). The contribution of biomass energy to future energy supply is likely to be driven mainly by a significant increase in energy demand, in particular in developing countries, and by environmental considerations. The widespread and diverse nature of biomass, its possible use for providing fuels, heat and electricity and logistic similarities between biomass and fossil fuel cycles are also likely to favour an increased use of biomass. International agreements are likely to set limitations on greenhouse gas emissions, and the substitution of fossil fuels by biomass can result in considerable avoided CO_2 emissions.

While traditional use of biomass is likely to continue to increase, a greater share of biomass energy is likely to come from more modern uses of biomass for the provision of fuels, heat and electricity. Modern systems, such as biomass integrated gasification gas turbine (BIG/GT) systems for heat and electricity generation, aim at an efficient and clean biomass use. Biomass may then possess a number of environmental advantages compared to other energy sources, fossil fuels in particular. Biomass energy systems may also present socio-economic advantages (e.g. employment creation, reduction of foreign expenditure, rural development). BIG/GT systems are currently at the demonstration stage and appear well suited for electricity production, district heat based co-generation and industrial co-generation.

The successful market penetration of biomass energy depends on a series of technical, economic, environmental and social issues which, in general, possess a strong regional dependency. In particular, the introduction of BIG/GT systems will depend mainly on the cost of energy which can be achieved by a mature BIG/GT system compared to alternative fuel cycles, and on the role of environmental and social considerations in decision and policy making.

The energy sector worldwide is facing an evolving decision and policy making framework. Increased liberalisation, accompanied by sensible policy measures, as well as aspects such as increased environmental awareness, may offer greater opportunities to biomass energy in the future. The competitiveness of biomass energy with other energy sources remains, however, a fundamental issue. Under current decision and policy making frameworks biomass is generally not competitive with more conventional energy sources.

The motive of the present work lies in the lack of comprehensive studies addressing the economic and environmental analysis of biomass fuel cycles within a framework for assessing the potential contribution of biomass energy to a more sustainable energy path at a regional level.

A number of authors have discussed the technical and economic performance of biomass gasification systems (see for example Kaltschmitt et al., 1998; Faaij et al. 1995; Bridgwater, 1995 and Williams and Larson, 1993) and others provide analyses of gasification-based biomass fuel cycles (see for example Faaij et al. 1998; Saez et al. 1998 and CEC, 1998a and b). The studies are generally based on hypothetical fuel cycles, focus on particular stages of the fuel cycle, and do not present a detailed integrated analysis of the biomass potential and the technical, economic, environmental and sustainability issues. Also, there is lack of a thorough comparison with competing conventional fuel cycles and of a discussion of the decision and policy issues in relation to gasification-based biomass fuel cycles at a regional level.

7.2 Aim and objectives

The aim of the work is to develop a framework for assessing the potential and performance of gasification-based biomass fuel cycles, for their comparison with selected reference conventional systems, and for decision and policy analysis at a regional level.

The analytical framework builds on the concepts of fuel cycle analysis (an extension of the concept of life cycle analysis), external costs and benefits, and sustainability. It integrates economic and environmental considerations and relies on the development of a database and model providing an integrated fuel cycle inventory of costs, resource use, emissions and employment.

Three site specific case studies are analysed, all based on circulating fluidised bed gasification integrated with combined gas and steam turbine cycles, and characterised by different fuels (energy crops and residues) and different policy settings (UK, Sweden, Brazil). Reference systems are selected for each of the regions considered for comparison with the biomass fuel cycles.

Effective decision and policy making requires information about the consequences of alternative options. A detailed technical, economic and environmental analysis will provide an assessment of the state of the technology, identify aspects of the fuel cycles which require improvement, and provide decision and policy-makers with key economic and environmental parameters to support decision and policy making. The decision and policy making framework needs to be addressed to identify both the requirements and opportunities of biomass fuel cycles. The objectives of the analysis are to:

- discuss critical technical issues and calculate the resource use, costs[3], emissions and employment inventory of gasification-based biomass fuel cycles in Europe and Brazil;
- identify and assess priority environmental impacts, and quantify, where possible, external costs and benefits;
- discuss the total costs and benefits and sustainability of gasification-based biomass fuel cycles;
- produce a decision and policy analysis based on the assessment of total costs and benefits and on sustainability considerations, and discuss the implementation requirements and opportunities of gasification-based biomass fuel cycles.

The study is innovative in its analysis of different promising gasification-based biomass fuel cycles in specific regional contexts. It provides technical, economic and environmental information of value with regard to the different fuel cycles, assesses their costs and benefits and their requirements and opportunities within the particular regional contexts. The study provides a basis for assessing the feasibility and economic and environmental viability of gasification-based biomass fuel cycles and for developing policies aimed at their support.

The principal stages of the work consist of:

- an introduction to modern biomass energy systems, to the concepts of fuel cycle analysis, external costs and benefits and sustainability, and to decision and policy making frameworks;
- the definition of the analytical framework: systems boundaries; priority impacts; resource use, costs, emissions and employment inventory; methods for assessing environmental external costs and benefits; sustainability considerations; and decision and policy making issues;
- a detailed description and discussion of three region-specific case studies ((a) short rotation coppice (SRC) and forestry residues for gasification-based electricity generation in the UK, (b) forestry residues for gasification-based district heating and electricity generation in Sweden, and (c) sugarcane residues for gasification-based process steam and electricity generation in the Brazilian sugar and alcohol industry)

[3] All costs used in the analysis are expressed in € (EURO) and refer to 1995 ECU values. The following conversion factors apply: 1€ = 1.308US$ = 0.829GB£ = 9.332SEK = 1.406R$

and of the reference conventional systems (coal, natural gas and hydro in Sweden, coal and natural gas in the UK, and biomass combustion and natural gas in Brazil);

- an analysis of the three case studies within the proposed analytical framework;
- the discussion of the feasibility, total costs and benefits, and sustainability of gasification-based biomass fuel cycles in relation to the reference systems and the implications for decision and policy making.

The analytical framework is intended to provide a useful guide for the assessment of biomass fuel cycles other than those analysed in this study. It includes a database and model providing an integrated fuel cycle inventory of costs, resource use, emissions and employment of gasification-based biomass fuel cycles, which is designed to allow future adaptation to other biomass fuel cycles and regional contexts.

7.3 Brief description of the work

The choice of the biomass sources is based on their estimated importance as potential fuels. The regional case studies have been selected based on the existing or potential development of the fuel cycles at those sites. The UK case study consists of a biomass integrated low pressure circulating fluidised bed gasification combined cycle plant (LP-BIG/CC) fuelled with wood chips from SRC and forestry residues. The Swedish case study consists of a biomass integrated high pressure circulating fluidised bed gasification combined cycle plant (HP-BIG/CC) fuelled with wood chips exclusively from forestry residues. The UK plant is under construction while the Swedish plant is operating as a demonstration plant. The Brazilian case study considers low or high pressure circulating fluidised bed gasification combined cycle systems at sugarcane mills fuelled with sugarcane residues, consisting of bagasse and residues from the harvesting of unburned cane (dry and green leaves and tops). Current availability of sugarcane harvest residues is low because of the common practice of burning the fields prior to manual harvesting, and where the cane is harvested unburned the residues are left in the field. The exploitation of these residues in conjunction with bagasse could have a great potential as a sustainable energy source. Although gasification is being discussed as a promising option for co-generation in the sugarcane industry, there are no projects actually being implemented at present.

The biomass fuels considered present different degrees of novelty. Forestry residues are an important source of fuel in Sweden and much experience has been gained over the last decade in their exploitation. The technologies for collecting, chipping and transporting the biomass fuel are commercially available.

Short rotation coppice, used as biomass fuel in the UK case study, is still at the early stages of development as a source of energy, with just over 200 ha currently planted in the UK. The greatest experience in Europe with SRC is in Sweden where about 16,000 ha have been planted. Trials with different species and planting densities are underway in the UK. Conventional farming machinery can be used for certain activities involved in short coppice growing, but specific equipment (e.g. planters, harvesters) is also being developed and is becoming commercially available.

Residues from the sugarcane milling process (bagasse) are widely utilised in the sugarcane industry to generate heat and electricity to satisfy the mills' electrical and mechanical power needs. However, there is considerable scope for a more efficient use of bagasse. The Brazilian case study also considers the potential of collecting harvest residues to complement bagasse for heat and power generation. Little experience exists worldwide on the collection of residues left in the fields after the harvesting of unburned cane, and field test are currently under way in Brazil.

Gasification-based power generation technology is currently at the demonstration stage with pending technical and economic uncertainties. A careful assessment of the technical status, economic competitiveness and environmental performance of the fuel cycles considered will reveal barriers and opportunities to their implementation. The consideration of reference systems makes it possible to emphasise the advantages and disadvantages of the gasification-based biomass fuel cycles specifically for the regions considered.

The comprehensive approach of the analytical framework, addressing technical, economic and environmental issues, provides a detailed picture of the advantages and problems associated with the biomass fuel cycles considered and of the improvements required. The technical, economic and environmental analysis, together with the discussion of the total costs and benefits and sustainability of the fuel cycle provide the tools for discussing decision and policy making issues. These emphasise the barriers and opportunities for the implementation of gasification-based biomass fuel cycles.

7.4 Synopsis

This chapter provides an introduction to modern uses of biomass for energy. It gives an overview of current biomass uses and potentials, different sources and types of biomass, conversion technologies for modern biomass use, and the stages typical of biomass fuel cycles. It introduces issues relevant to modern uses of biomass for energy and to decision and policy making, and provides an outlook on the future of biomass energy.

Chapter 2 defines the analytical framework for the study, providing the tools to achieve the thesis' aims and objectives. It begins with a brief description of the regional context information which influences the economic and environmental performance of the fuel cycles and is of key importance for the decision and policy analysis. Then it provides a description of the economic and environmental analysis, which represents the core of the analytical framework, and of the concepts of fuel cycle analysis, input-output analysis, and externalities on which it is based. A section on the issues relevant to the sustainability of fuel cycles follows, which provides the basis for discussion of the sustainability of the fuel cycles considered. A discussion on the issues relevant to the decision and policy analysis, which draws on the regional context, on the economic, environmental and employment analysis and on the sustainability analysis, concludes the chapter.

Chapter 3 consists of an overview of gasification-based biomass fuel cycles. It provides background on the fundamentals of gasification, including gasification and gasifier types. A detailed description of the activities characteristic of biomass integrated gasification systems for heat and electricity is provided, from the storage of the biomass fuel at the facility through gasification and conversion to the disposal/recycling of the waste. The chapter also includes an overview of the economics of biomass gasification, which will then be discussed in more detail in Chapters 5 and 7. It concludes with a discussion on the constraints and opportunities affecting the development of biomass integrated gasification systems.

Chapter 4 introduces the Swedish and UK case studies. It begins with information on the framework for biomass energy exploitation, including biomass potential, national and local policies and key players, and a description of the regional environmental and socio-economic context. Then, it provides a detailed description of the different stages of the two gasification-based biomass fuel cycles, the Värnamo Plant in Värnamo, Sweden, and the ARBRE Plant in Eggborough, UK. The fuel cycle description discusses their strengths and weaknesses and provides the basis for the economic and environmental analysis, including the identification of the fuel cycles' main impacts. Finally, reference systems are defined, which will serve as a basis for comparison to assess the economic and environmental performance of the biomass fuel cycles.

Chapter 5 provides a detailed economic, environmental and resource use analysis of the Värnamo and ARBRE fuel cycles and extends it to the short-term development of similar fuel cycles. It begins with a detailed economic analysis, including employment, of the biomass production, transport and conversion stages of the fuel cycle as well as of the cost of heat and electricity generated. This is followed by a discussion on the sensitivity of the biomass fuel and heat and electricity costs to different parameters and on short-term projections of the costs and their comparison to reference energy costs. A discussion on direct and indirect employment concludes the economic analysis. The environmental analysis which follows discusses in detail the direct and indirect atmospheric emissions from the biomass and reference systems. Issues of soil quality, water use and quality, sewage sludge application, biodiversity and amenity are also discussed for the biomass fuel cycles. The chapter concludes with an energy analysis of the biomass and reference fuel cycles.

Chapter 6 introduces the Brazilian case study. It begins with an introduction on sugarcane residues as a source of energy and the energy potential it represents for Brazil, and with an analysis of the potential for electricity surplus at the mills based on their characteristics and on the introduction of BIG/CC systems. The chapter then provides information on the framework for biomass energy exploitation, including an overview of energy demand and supply, a discussion on the rapidly evolving energy sector and information on key players, and a description of the regional environmental and socio-economic context. This is followed by a detailed description of the different stages of gasification-based fuel cycles based on sugarcane residues. The fuel cycle description discusses strengths and weaknesses and provides the basis for the economic and environmental analysis, including the identification of the fuel cycles' priority impacts. Finally, reference systems are defined, which serve as a basis for comparison to assess the economic and environmental performance of the biomass fuel cycles.

Chapter 7 provides a detailed economic, environmental and resource use analysis of the Brazilian case study. It begins with a detailed economic analysis, including employment, of the biomass production, transport and conversion stages of the fuel cycle as well as of the cost of heat and electricity generated, for different size mills. A discussion on direct employment concludes the economic analysis. The environmental analysis focuses on the direct atmospheric emissions from the biomass and reference systems. The chapter concludes with an energy analysis of the biomass and reference fuel cycles.

Chapter 8 discusses the externalities and total costs of the three biomass fuel cycles as well as their sustainability in comparison with the reference fuel cycles. The chapter begins with a review of the externalities of energy, including the externalities of biomass energy. Then it provides a detailed discussion on the externalities of Värnamo, ARBRE and Brazilian sugarcane residues fuel cycles as well as the reference systems, including a discussion of damage and avoidance costs of CO_2 emissions. This is followed by a discussion on the total costs and benefits of gasification-based biomass fuel cycles compared to conventional systems. A discussion on fuel cycle sustainability, in particular biomass fuel cycles, concludes the chapter.

Chapter 9 brings the work to a conclusion with a summary of its main findings and a discussion on the future of gasification-based biomass fuel cycles.

CHAPTER 2

THE ANALYTICAL FRAMEWORK

1 Introduction

The analytical framework aims to provide the tools to achieve the thesis' objectives, that is the assessment of the performance of gasification-based biomass fuel cycles, their comparison with selected reference conventional fuel cycles and a discussion on decision and policy-making at a regional level. It must address the important issues associated with the modern use of biomass for energy, in particular technical, economic and environmental issues, which influence decision and policy making and the successful implementation of gasification-based biomass fuel cycles.

It will provide:

- an analysis of the regional context;
- economic, environmental and resource use data for the biomass and reference fuel cycles;
- a discussion of the total costs, including externalities, of the biomass and reference fuel cycles;
- a discussion on the sustainability of the biomass fuel cycles;
- a decision and policy analysis addressing the requirements, opportunities and barriers for the successful implementation of the gasification-based biomass fuel cycles considered.

The analytical framework (Figure 3) is based on the concepts of fuel cycle analysis, externalities and sustainability. The state-of-the-art, shortcomings, potential extension and application to the present work of these concepts are discussed in this chapter, and their integration into a framework for the assessment of the biomass fuel cycles considered is illustrated.

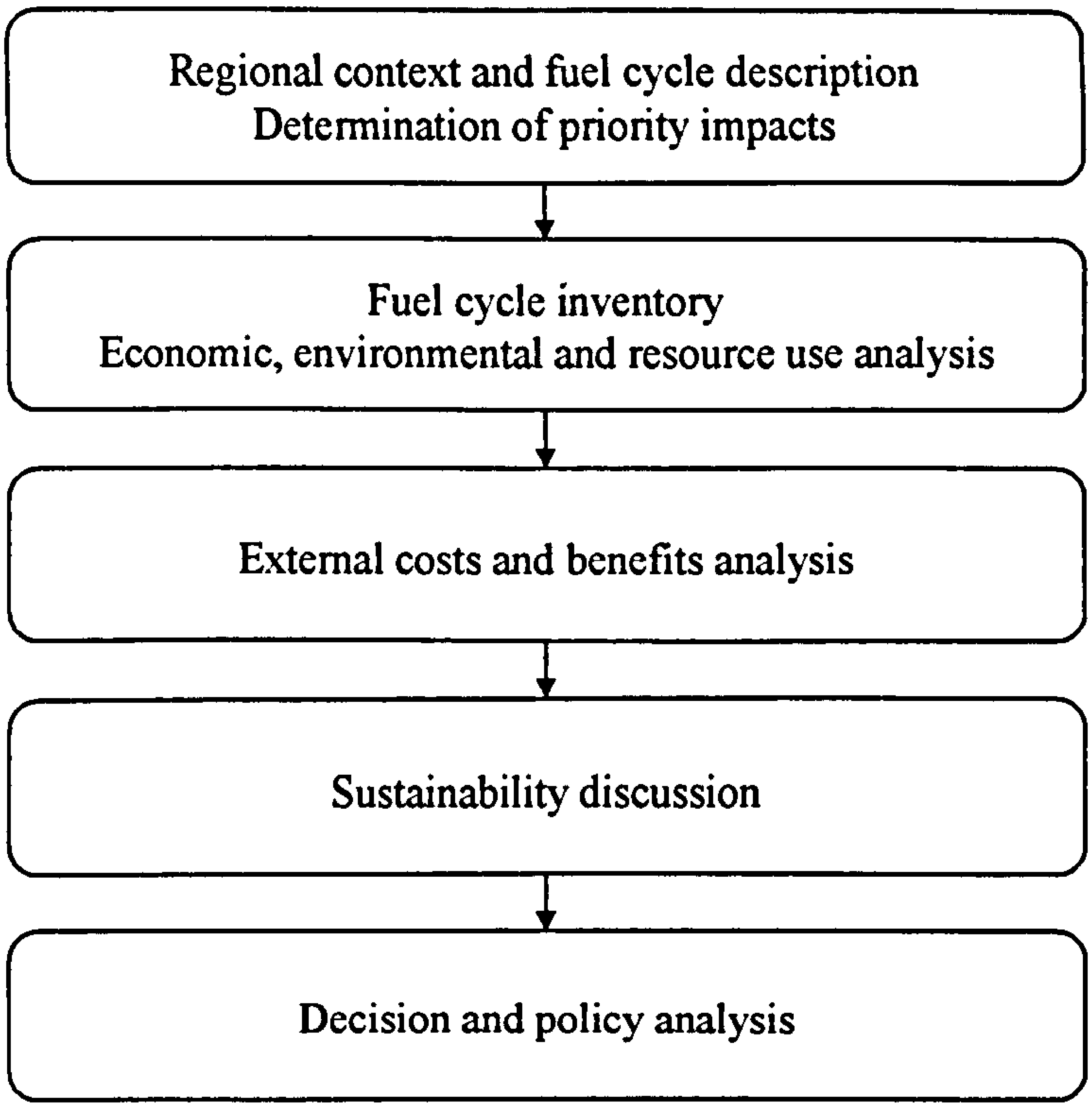

Figure 3: The analytical framework

2 The regional context

The regional context, which is specific to the case studies, influences the economic and environmental performance of the fuel cycles and is of key importance for the decision and policy analysis. Information on biomass potential, state of the environment, and relevant socio-economic and regulatory/policy aspects are provided as part of the regional context. Together with the detailed analysis of the fuel cycles it will allow the identification of opportunities and barriers to the implementation of gasification-based biomass fuel cycles.

3 Economic, environmental and resource use analysis

The basis of the analytical framework consists of the economic, environmental and employment analysis of the fuel cycles, based on a life cycle analysis (LCA) methodology. LCA, a systematic tool generally used to provide information on the environmental consequences of production processes, has been extended to include costs and employment. The extension of the LCA is meant to cover economic and environmental parameters which are important in the assessment of the viability of the fuel cycle.

3.1 Life cycle analysis

The Society of Environmental Toxicology and Chemistry has been active in developing LCA and defines it as follows (Consoli et al., 1993):

> *LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impacts of those energy and materials uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvement. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling and final disposal.*

LCA provides a framework within which the impacts of production systems can be assessed. It has generally focused on environmental burdens, with few studies examining socio-economic aspects of the system considered (see for example Kuemmel et al., 1997). The primary aim of LCA studies has been to provide an exhaustive inventory of environmental burdens and to link them to a series of impact categories (see for example Kaltschmitt et al., 1997). This allows for a direct comparison of emissions or impact potentials (e.g. the acidification potential which expresses the various acidifying agents as SO_2-equivalent emissions) from different systems without providing a specific assessment of the impacts. While emissions inventory and impact classification stages of a LCA are generally agreed upon, the impact assessment stages are still a subject of debate (see for example Heijungs et al. 1992; Consoli et al., 1993; Kuemmel et al., 1997).

A fuel cycles analysis (FCA) is a form of LCA which analyses the entire life cycle of a particular energy conversion route, from the production of the fuel through its energy conversion to the disposal of wastes from the process. The analytical framework proposed here uses a LCA approach to study gasification-based biomass fuel cycles.

The principal stages of a LCA are:

- Goal and scope definition;
- Inventory analysis;
- Impact assessment;
- Improvement assessment;
- Analysis and interpretation of results.

The LCA approach allows for a detailed analysis of the fuel cycle emphasising its strengths and weaknesses, and it will integrate a detailed economic and environmental analysis. A conventional LCA approach is limited with respect to the objective of this study, but it provides a consistent and transparent methodology for deriving an inventory of costs, emissions and labour requirements of the fuel cycle, and proceeding with an economic and environmental analysis.

The goal and scope definition process is the first stage of a LCA. The goal of the LCA approach in the present work is to provide an analysis of gasification-based biomass fuel cycles based on economic, environmental and resource use parameters. The scope definition process defines the fuel cycles and their boundaries, as well as the data requirements and assumptions made. The general structure of the systems studied is shown in Figure 4 and a more detailed definition of the fuel cycles will follow in the description of the case studies (see Chapters 4 and 6).

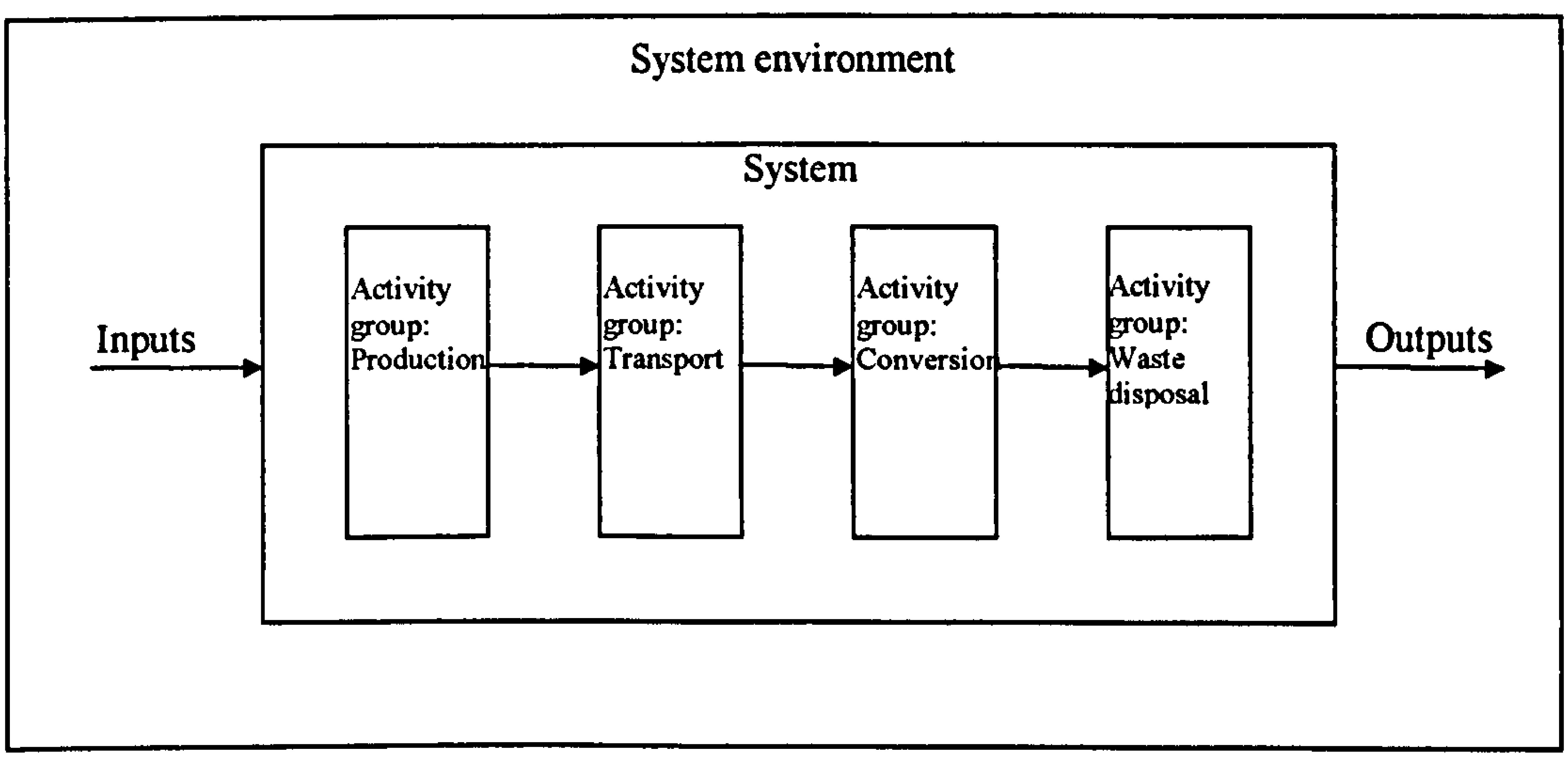

Figure 4: General structure of the systems studied

The scope definition process will also screen the possible fuel cycle impacts to determine the priority impacts, i.e. those impacts which are likely to be significant - based on our judgement and current knowledge - and which will be considered in the analysis. Fuel cycle activities lead to a variety of impacts. Table 1 provides a list of impact categories, classified as environmental and non-environmental, and Table 2 contains a list of related impacts. The list of impact categories and impacts is not meant to be exhaustive but should capture any effects which are likely to have significant impacts in the case of biomass and reference fossil fuel cycles. Based on a preliminary analysis of the fuel cycles, the boundaries should be chosen so as to include all significant impacts. The relevant impact categories associated with the fuel cycles selected as case studies are discussed as part of the description of the fuel cycles in Chapters 4 and 6.

Table 1: Examples of impact categories leading to potential externalities

Environmental	Non-environmental
• Human health • Ecotoxicity (impacts of noxious substances on flora and fauna) • Acidification • Eutrophication • Soil quality • Climate change • Amenity (e.g. noise, odours and visual impacts) • Biodiversity	• Resource use • Employment • Security and reliability of supply • Effects on Gross Domestic Product • Rural development

Table 2: List of impacts associated with impact categories

Impact categories	Impacts
Environmental	
Human health[4]	Acute mortality Chronic mortality Morbidity (e.g. respiratory) Injury
Ecotoxicity	Forestry and crop yield loss Terrestrial and aquatic biodiversity loss
Acidification	Forestry and crop yield loss Terrestrial and aquatic biodiversity loss Damage to materials
Eutrophication	Aquatic biodiversity loss
Depletion of ozone layer	Morbidity (cancer)
Photochemical oxidant formation	Morbidity (respiratory) Forestry and crop yield loss Damage to materials
Climate change[5]	Coastal flooding Gain/loss of agricultural production Famine Biodiversity loss Other damage from extreme weather events
Rural amenity (e.g. noise, odours and visual impacts)	Nuisance Loss of property value Loss of amenity to visitors

[4] The human health impacts considered in the ExternE project consist of mortality and morbidity effects associated to particulates, acid aerosols and ozone.

[5] See Fankhauser, 1995, for a more detailed description of impact categories.

Non-environmental	
Resource use	Resource depletion National balance of payments
Employment	Reduced public expenditure Fulfilment of human needs
Security and reliability of supply	Price shocks Military expenditure Loss of production due to power shortage
Effects on Gross Domestic Product	Increase/reduction of GDP
Rural development	Stabilisation of rural populations Increased wealth of rural populations

Goal and scope definition is followed by the inventory analysis. While LCA is generally concerned with environmental burdens, the scope of the present work is to capture resource use and environmental aspects of the fuel cycles studied, and the inventory provides figures on energy flows, costs, emissions and labour requirements. These aspects are considered since they are likely to be of importance to decision and policy making.

A database and model have been created, as part of the study, to produce the inventory. A detailed description of the database and model is provided in Annex 1 and its structure is shown in Figure 5. An input-output model is used separately to calculate indirect economic and environmental parameters (see Section 3.2). The fuel cycle inventory (FCI) is the first immediate outcome of the fuel cycle analysis, and the outcomes can be presented for the different fuel cycle activities, aggregated for different stages of the fuel cycle or for the fuel cycle as a whole.

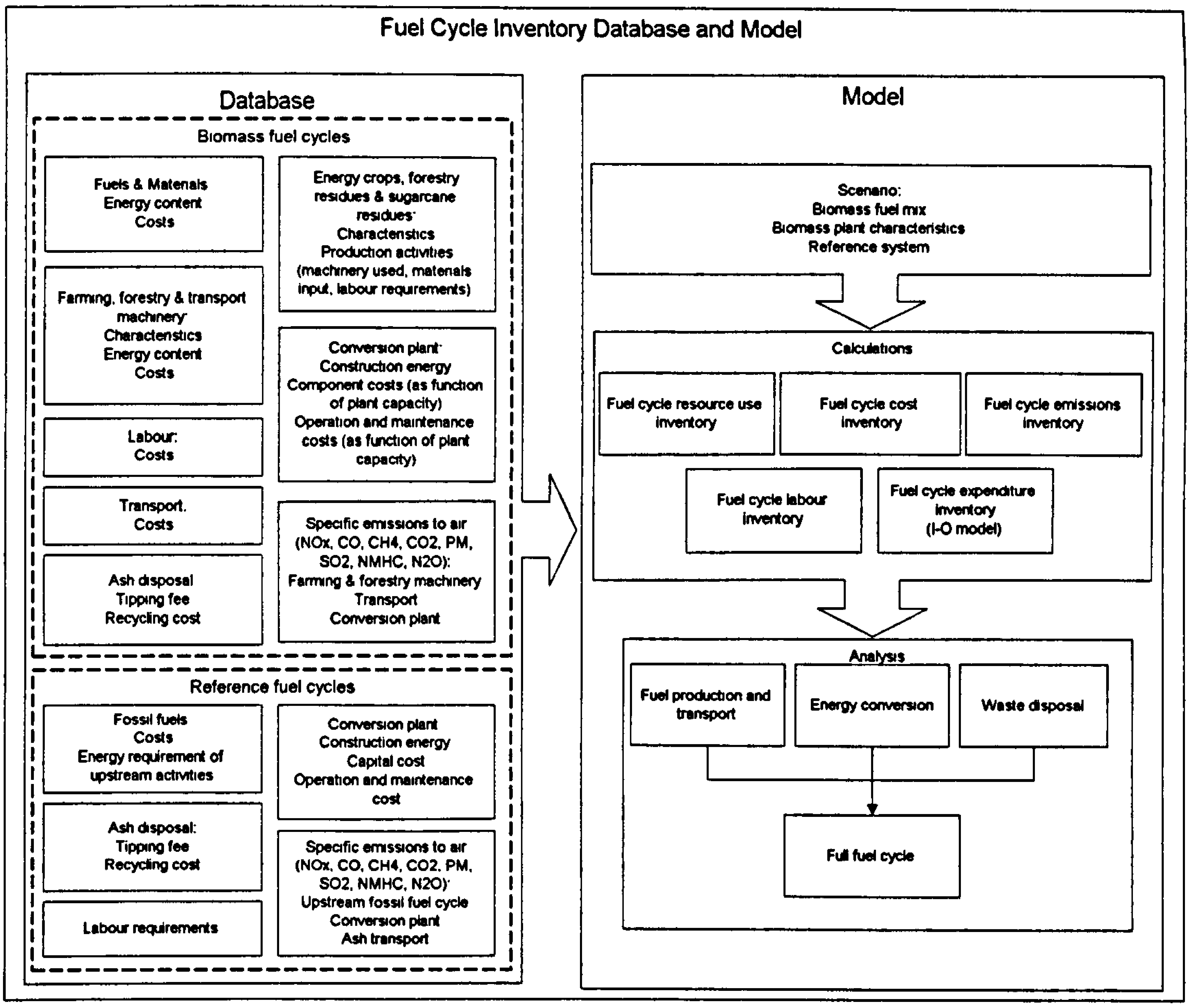

Figure 5: Database and model structure

The different forms of useful energy generated (i.e. heat and electricity) by the biomass fuel cycles lead to issues related to the choice of reference systems and to the allocation of economic and environmental parameters to the different products. The choice of the reference systems and the way in which burdens are allocated are likely to have an important effect on the conclusions drawn from the comparison of the systems. Issues of allocation and comparison have been dealt with extensively in other studies (see for example Clift et al. 1997; ISO, 1997 and CEC, 1998a). The comparison between the biomass and reference fuel cycles is based on a systems approach, that is the reference fuel cycle has been defined so that it provides the same service (i.e. heat and electricity supply) as the biomass fuel cycle. Systems can then be compared based on economic and environmental parameters associated with the totality of the services provided, for example, based on annualised costs and on annual emissions of the systems. In order to allow for comparison with economic and environmental figures from other sources, the outcomes of the economic and environmental analysis have also been expressed per unit of energy output. Allocation of economic and environmental parameters to heat and electricity is done on an energy and exergy basis and the consequences of such allocation are discussed more in detail in the case studies' economic and environmental analysis.

The FCA could end with the establishment of the inventory and the classification of its outcomes according to the impact categories. The inventory would then be used as the basis for a direct comparison between fuel cycles, or to assess the performance of the fuel cycle with regard to limit values. However, it is difficult to express judgement on a fuel cycle and on its comparison to other fuel cycles based on a FCI alone because no actual knowledge is available on the magnitude of the impacts or on how to deal with trade-offs between different impact categories.

The FCA framework then proceeds to an assessment stage in which evaluation and analysis tools can be used to assess the impacts and trade-offs between impact categories, and provide aggregate 'scores' for the fuel cycles. The inventory can be used to determine impacts, social costs and sustainability indicators to assess the fuel cycles and to compare them to other fuel cycles. The assessment stage in the present study will attempt, to the extent possible, an evaluation of the total costs and benefits (see Section 3.3) of the fuel cycles through a quantification of the environmental impacts followed by their monetary valuation. A discussion on the sustainability (see Section 4) of the fuel cycles will be carried out as part of the assessment stage. The inventory and assessment stages will lead to a discussion on the improvement potential of the biomass fuel cycles. Also, the outcomes of the inventory and assessment will be compared for the fuel cycles and be used as a basis for the decision and policy analysis.

A LCA approach is useful because it allows for a transparent and detailed view of the fuel cycle. It allows to determine the contribution of each activity to the full fuel cycle for the economic and environmental parameters of interest. It allows to target the activities with the highest burdens for improving the fuel cycle and, similarly, allows to determine activities which have little or negligible impacts. Also, a preliminary analysis prior to a proper assessment of the fuel cycles can be performed based on the inventory results. The inventory is useful to provide a picture of the magnitude of the economic and environmental parameters and how they compare for different fuel cycles and with regard to recommended or regulatory limits. The assessment of the fuel cycles provides a better analysis of the trade-offs between fuel cycles and a discussion of their sustainability which are useful for discussing decision and policy making issues.

3.2 Energy analysis

The energy analysis is part of the fuel cycle analysis and is used for assessing the total amount of primary non-renewable energy required to provide a determined quantity of useful energy (i.e. heat and/or electricity). It assesses resource use in the form of non-renewable energy, identifies areas where non-renewable energy consumption is high and efforts could be made to reduce it, and allows to compare different fuel cycles (or fuel cycle variations) with regard to non-renewable energy use. For example, it is possible to determine how variations in yield and the use of different technologies can affect the energy balance. Other factors, economic in particular, are likely to play a greater role in decision making. Nevertheless, energy analysis can serve as a complement to economic analysis.

3.3 Input-output analysis

An input-output analysis is carried out to investigate the significance of indirect effects of the fuel cycle on the environment and employment. Indirect effects are those which result from activities not considered within the fuel cycle system boundaries and which provide inputs to the fuel cycle e.g. emission and employment generated by the agrochemicals industry.

Input-output analysis is a standard economic tool first introduced by Wassily Leontief in 1936. The underlying idea is that the output of each production sector in the economy can be described in terms of the amounts purchased by other production sectors (intermediate demand) and the amounts purchased by final consumers (final demand). A matrix structure (input-output tables) is used to describe the flow of goods and services through the economy by listing all transactions inside the production sector and between the production sector and final demand in monetary terms on an annual basis. They illustrate the relationship between producers and consumers i.e. where an output of a particular sector goes to satisfy final demand, and the interdependence among the different sectors i.e. where an output of a particular sector is used as an intermediary input to another sector.

The use of input-output models for environmental analysis has been suggested and applied by various researchers (see for example Lave et al., 1995). The Fraunhofer

Institute for Systems and Innovations Research (Hohmeyer and Walz, 1992) developed a model and software, known as the EMI model, for the estimation of employment and emissions based on an enhanced input-output analysis for Germany. The model has been developed further at the Centre for European Economic Research - ZEW. Based on economy wide input-output tables, employment coefficients and a large database containing specific emission coefficients, the software makes it possible to estimate indirect employment effects and indirect emissions of a number of relevant air (CO_2, CO, NO_x, SO_2, VOCs, and particulates) and waste water pollutants and of many types of solid waste.

In this study, OECD input-output tables for the UK and Sweden for the year 1995 are used as input to the EMI model. Furthermore, the shares of different energy sources were adapted accordingly. However, German coefficients for labour intensity and sector specific emissions are used due a lack of country specific data for the UK and Sweden. Obtaining such data and adapting them for use with EMI is a costly task and is beyond the scope of this study. The use of German labour and emission coefficient for industrial processes should provide a good indication of indirect effects to be expected in the UK and Sweden.

The EMI model is used to determine the indirect environmental and employment effects of expenditure associated with the biomass and reference fuel cycles. For this purpose, the total expenditures over the entire fuel cycle lifetime is distributed among the different economic sectors (35 sectors for the OECD input-output tables) and fed into the EMI model.

3.4 External costs and benefits

External costs and benefits are used as part of the assessment stage of the fuel cycles. The concept of externality is part of the neo-classical theory of welfare economics and was first established by Arthur Pigou (Pigou, 1920). Externalities are the result of market failures which lead to certain effects of economic activities not being accounted for in economic transactions. The consideration of these effects is important as it accounts for the effects of economic activities on society as a whole as opposed to only on the parties involved in the economic transaction, and therefore reflects social preferences as opposed to individual preferences.

The social costs and benefits of an economic activity consist of the sum of the private (internal) and external costs and benefits, and the aim of social costs and benefits analysis is for products and services to reflect their true costs to society. Externality adders can be added to the private costs of goods and services to reflect their true costs. Social costs, as opposed to private costs, should allow for an economically efficient allocation of resources such that the economic welfare of society and individuals is maximised simultaneously. This relies on the assumption of perfect information, perfect markets and rational (i.e. aiming at maximising individual utility or profit) behaviour on the part of the players. In fact, there are shortcomings to all three of the previous assumptions, making optimal allocation only possible in theory.

According to the neo-classical theory of welfare economics, the optimal level of pollution abatement (Q) is such that the marginal cost of emissions abatement is equal to the marginal cost of pollution damage. For all values of emissions different than Q, the theory implies that there is a welfare loss. For values of abatement below Q this welfare loss consists of an excess of damage costs and for values of abatement above Q it consists of an excess of abatement costs. In both cases the allocation of resources is not considered optimal, with resources being used which could, in theory, find better use elsewhere in the economy.

Distinction is often made between environmental and non-environmental externalities. Environmental externalities are meant to consider all effects of human economic activity on the natural and man-made environment. However, the concept of environmental externality is strongly anthropocentric, focusing on direct and indirect effects on human health and amenity. Non-environmental externalities are broader in scope and may include issues such as value added to the economy, employment effects, resource use, and security of supply. Careful consideration is required when assessing if an effect of an economic activity is an externality as this may not be evident, especially in the case of non-environmental externalities.

The main reasons for a monetary valuation of impacts are:

- The internalisation of externalities to eliminate market distortions and achieve a more efficient allocation of resources, thus improving economic efficiency;
- The introduction of market based mechanisms (e.g. environmental taxes) as a more economically efficient way of achieving environmental objectives than command-and-control measures (Pearce et al., 1989);
- The achievement of weak sustainability[6] through the consideration of social costs and benefits;
- The use of money as a common measuring rod (with which different players are familiar) for the quantification of impacts.

The objective of the social costs and benefits analysis in this study is to:

- Discuss the state of the art in energy externalities, biomass energy externalities in particular;
- Identify, discuss and value, to the extent possible, the external costs and benefits associated with the different gasification-based biomass fuel cycles;
- Compare the external costs and benefits of gasification-based biomass fuel cycles with those of conventional reference fuel cycles;
- Discuss the limitations of external costs and benefits valuation and the necessity of their integration within a broader sustainability context;
- Discuss the possible role of external costs and benefits in decision and policy analysis with regard to the biomass fuel cycles and the regional contexts considered.

3.4.1 The externalities of energy

The energy sector is a major source of environmental and non-environmental externalities (Table 1). Therefore, the consideration of the externalities in decision and policy making with regard to energy is fundamental to reduce its negative impacts and move towards a more sustainable energy supply and use.

Externalities occur at all stages of a fuel cycle[7]. The externalities of energy can be reduced by improving fuel cycles, switching between fuel cycles, a more efficient end-

[6] Two forms of sustainability are often referred to: weak sustainability and strong sustainability. The first assumes that man-made and natural capital are perfect substitutes and the latter assumes that the ecosystem possesses fundamental life-sustaining functions which cannot be substituted by man-made capital.

use of energy and reductions in energy consumption. The ultimate goal of externalities valuation is to achieve an economically efficient allocation of resources through the integration of externalities in energy prices. Given the state of the art of externalities valuation, we are still far from being able to use externalities in search of Pareto optimal solutions (admitting that markets operate perfectly!). However, the valuation of externalities - and the process of assessing externalities generally - is useful for providing an indication of damages/benefits associated with different energy options, for assessing trade-offs between different energy options and for ranking energy options. It can thus also serve as a basis for the introduction of economic instruments to reflect the social costs of energy.

The monetary valuation of environmental externalities now seems to be the dominant paradigm in the comparative environmental appraisal of energy options (Stirling, 1997). However, the path to assessing externalities is mined with difficulties and uncertainties.

3.4.2 Approaches to externalities assessment

The determination of the external costs and benefits of fuel cycles is characterised by three main stages: identification, quantification and monetisation of the impacts.

Two methodologies are commonly used to determine the externalities associated with fuel cycles and are based on top-down or bottom-up approaches. Most of the earlier externalities studies employ a top-down approach where generic damage costs are estimated at a national level for different impact categories e.g. damage to forests, and are then attributed to various emissions e.g. SO_2, to determine (based on an emissions inventory) an average external cost per unit of emission. The external cost per unit of energy is finally obtained on the basis of generic emissions from different fuel cycles (Hohmeyer, 1988; Friedrich and Voss, 1993; Pearce, 1995 and Ott, 1996). The top-down approach is generally based on highly aggregated data for damages and emissions. It may be suitable to provide a first indication of the environmental externalities of energy where sufficient data is available on the state of the environment

[7] A fuel cycle is defined as consisting of all activities involved in the supply of thermal or electrical energy to a end user and consists of the following principal activity groups: primary fuel production and transport, conversion to heat and electricity, and electricity and heat distribution. In the case of energy supply to the transport sector, the fuel cycle consists of primary fuel production, transport and refining, fuel distribution, and conversion to mechanical power. Renewable fuel cycles, such as wind, solar and hydro, do not possess upstream fuel production and transport stage and the fuel cycle consists uniquely of conversion and transport and distribution stages. Energy saving measures could be considered as a fictitious fuel cycle in which energy instead of being generated is saved (negawatts).

to estimate specific impacts resulting from emissions of pollutants to the environment. It does not, however, allow for the assessment of the marginal effects of additional energy supply which are usually of interest for decision making and planning purposes.

The bottom-up approach is also known as *impact-pathway approach* or *damage-function approach* (DFA), and it allows for the calculation of marginal external costs. The approach can be generally applied to all sorts of impacts for which an impact-pathway can be defined. In the case of pollutants the approach begins with determining the quantity of emissions from a defined source, then makes use of dispersion models and exposure-response functions to determine the marginal damages resulting from the emissions. The final step consists of multiplying the marginal damages by their estimated monetary value. DFA studies are site specific and the marginal external costs obtained are in principle not transferable. The application of this methodology requires large quantities of data and is time consuming. The results of past studies have shown that externalities calculated using a bottom-up approach tend to be lower that those calculated using top-down approaches. In part this difference appears to be due to the limited consideration of synergistic effects between pollutants and the adoption of linear exposure-response functions in bottom-up studies. The more recent studies use this approach (RCG/Tellus, 1995; ORNL/RFF, 1994 and CEC, 1995 and 1998a).

A series of valuation techniques are used to assign monetary values to environmental impacts. *Market prices* can be used for the direct valuation of damages or benefits to commodities which are traded (e.g. damage to forests leads to the loss of timber which can be quantified). For environmental goods and services for which no direct market exists, economists have had to devise other valuation tools. A direct method consists of the *contingent valuation method (CVM)*, in which individuals are asked the *willingness to pay (WTP)* for improved environmental quality or the *willingness to accept compensation (WTA)* for environmental damage, thus creating a fictitious market for the goods and services considered. Non-market items can also be valued *indirectly* by examining changes in prices of traded commodities which are linked to them. *Hedonic valuation* looks at differences in prices of market-based goods e.g. housing prices, to determine the willingness to pay of individuals to avoid certain impacts. The *revealed preference method* infers what value individuals place on goods and services by observing their behaviour. For example, *travel-cost valuation* looks at individuals' expenditure to travel to places where a desirable environment may be experienced.

Where damage costs are difficult to determine using the above valuation techniques, or if the uncertainty of the values is judged to be too large, control costs have been proposed in some cases as a proxy for damage costs. Control costs can be determined by assessing the costs of achieving emissions reductions to specific levels (or also costs incurred for mitigating the damages). They do not give an indication of the externality but of what society would have to pay to avoid it. This may be useful in relation to impacts which are characterised by a high degree of uncertainty, as is the case with climate change.

3.4.3 The ExternE methodology

The most exhaustive study to date on the external costs of energy is the ExternE project which began as a collaborative effort between the EC and the US in 1991, and of which the European side completed a third phase in 1998 (CEC, 1995 and 1998a). The ExternE methodology (CEC, 1995) uses a bottom-up approach to determine the environmental external costs of fuel cycles (Figure 6).

The project has been principally concerned with the determination of impacts and externalities of air emissions from conventional thermal power plants, as these are believed to cause the most significant (i.e. priority) impacts in the case of conventional fossil fuel cycles. To determine the damages of atmospheric pollution, the dispersion and transformation of pollutants is modelled based on short-range and long-range atmospheric dispersion models. The local atmospheric dispersion model calculates the pollution increments for one hundred 10x10 km grid cells around the emission source. The regional atmospheric dispersion model calculates the pollution increments for 100x100 km grid cells across Europe. The pollution increments can be translated into impacts via exposure-response functions. ExternE has selected a large number of exposure-response functions (ERFs) relating impacts to the polluting species considered (e.g. effect of exposure to particulate concentration on acute mortality). The ERFs are the result of an extensive literature survey and are mostly based on recent epidemiological studies carried out across Europe (ExternE Phase III - CEC, 1998a). It is important to note that the exposure-response functions used are linear. The economic valuation of the physical impacts is carried out, based on a database of monetary values associated with the different impacts. The monetary values are based on different valuation techniques and have been obtained through a literature survey.

The EcoSense software developed within the framework of the ExternE project performs the external costs calculations for short-range and long-range atmospheric pollution from point sources. EcoSense requires input in the form of plant characteristics and location, emissions per unit flue gas volume, and meteorological data for the short-range dispersion model. The results are provided as a range of low and high cost estimates for damages to human health, damages to forestry and crops and damages to building material. The EcoSense model is used in this study to estimate the damages associated with atmospheric emissions from the fuel cycles considered. Key features of the model are its short-range and long-range atmospheric dispersion models, its database on ERFs and its database on monetary values of environmental impacts. Details on the dispersion modelling and databases are found in CEC (1995) and (1998a). An important difference between the last phase of the ExternE project and the previous ones resides in the valuation of mortality. In phase III, "values of life years lost" (VLYL) were defined in addition to the previously used "value of a statistical life" (VOSL). The VOSL valued premature deaths independently of age, while the VLYL considers changes in life expectancy and values the years of life lost instead of the number of premature deaths. The use of VLYL provides a more conservative valuation compared to the previously used VOSL.

The ExternE methodology is used within the present analytical framework to assess the damages of the atmospheric emissions from UK and Swedish biomass and reference fuel cycles, based on the results of the fuel cycle emissions inventory.

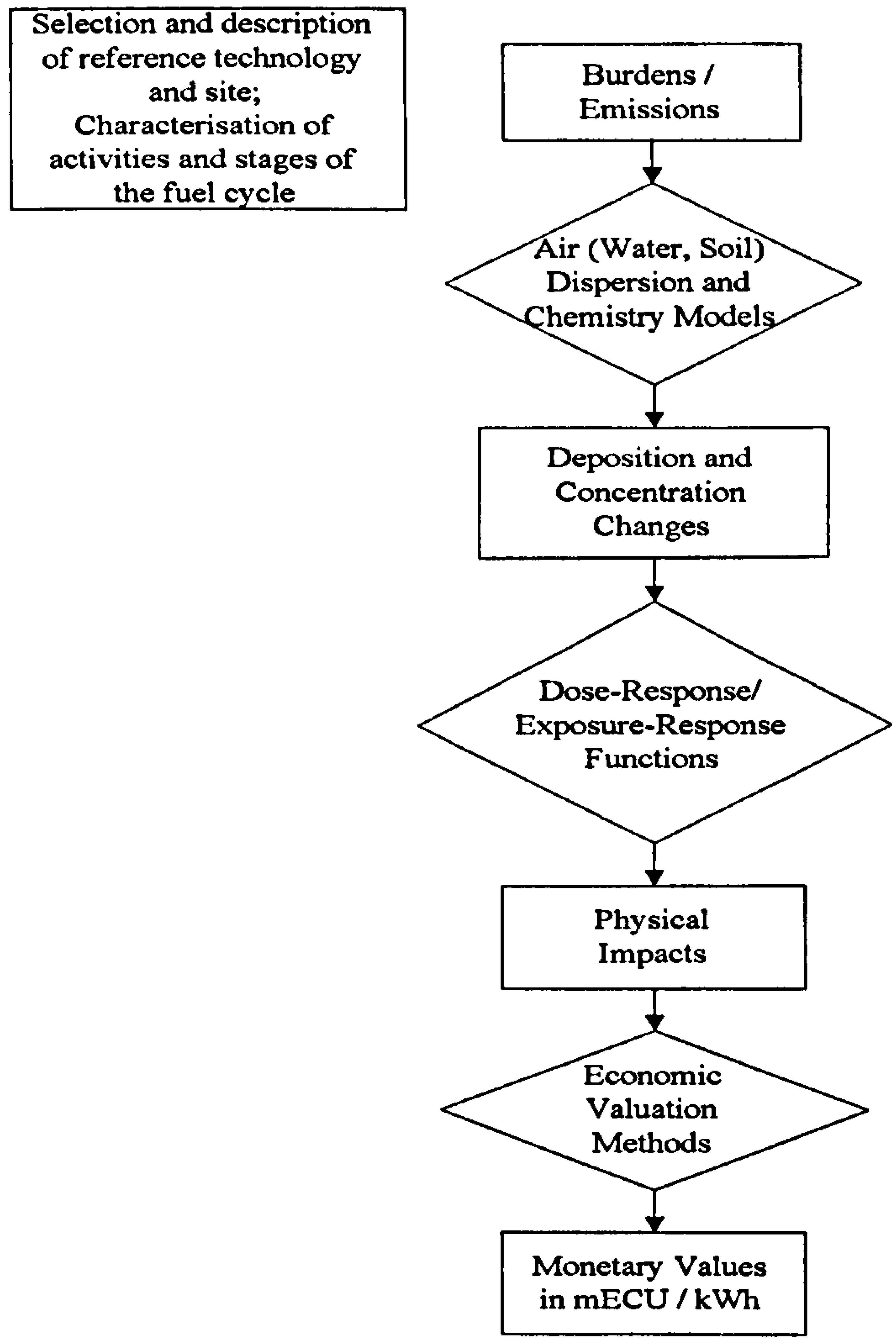

Figure 6: ExternE impact-pathway methodology (CEC, 1998b)

The ExternE methodology stresses three principles which are important in externality valuation. They are: transparency (i.e. clear description of method, assumptions and data used), comprehensiveness (i.e. consideration of all significant impacts and full account of their spatial and temporal effects), and consistency (i.e. allow for comparisons between different fuel cycles and sites).

3.4.4 Dealing with greenhouse gas emissions

ECOSENSE allows the modelling of the impacts of local and regional pollutants within Europe. A separate approach is needed to deal with the global effects of greenhouse gas emissions. The emission of these gases, CO_2 in particular, can be significantly reduced by using biomass instead of fossil fuels. However, the external costs of these emissions and the benefits of their avoidance compared to the reference fossil fuel cycles are difficult to estimate and uncertain.

Estimates of damage costs for greenhouse gas emissions vary by orders of magnitude in the literature. Variations in the estimates are a result of uncertainty over the type and magnitude of impacts, the impact categories considered by different valuation studies, the valuation method employed and the underlying economic assumptions. Damage cost estimates of the studies reviewed by the IPCC (1996) range between US$6 and US$221/tC for the period 1991 - 2030. Hohmeyer (1996) has shown that differences in the countries covered, in the value of a statistical life and in the discount rate cause monetary estimates of potential damage to vary by several orders of magnitude. The valuation of non-market damage and discounting remain the great unresolved issues. Categories and estimates of non-market damages vary greatly in the literature. Discounting of damages which may occur years from now and affect future generations remains an unresolved economic issue and a fundamental ethical question e.g. problems of intra and inter-generational equity.

The uncertainties and value judgements surrounding the valuation of climate change damages indicate that a standard economic approach, consisting of the search for an economically optimal solution based on the comparison of the marginal damage costs of climate change with the marginal benefits of actions taken to prevent them, is most likely not to be applicable nor appropriate. In the words of the IPCC Working Group III, "both the costs and the benefits may be hard, sometimes impossible to assess. This may be due to large uncertainties, possible catastrophes with very small probabilities, or simply lack of consistent methodology for monetising the effects." (IPCC, 1996).

The approach to dealing with climate change may be better sought by applying principles of ecological economics (Daly, 1996), advocating strong sustainability, rather than those of neo-classical economics. As a result, issues like climate change, for which there is evidence that impacts on future generations could be considerable, need to be treated in a precautionary fashion, by application of the precautionary principle. This implies that actions should be taken, although not necessarily justifiable in terms of traditional cost-benefit analysis, where there is sufficient reason to believe that the consequences of not taking action could be severe. The Kyoto Protocol, which aims at a 5.2% global reduction of greenhouse gas emissions by 2012 compared to 1990 levels, represents a move in this direction, although much work is yet needed to achieve consensus over the risks associated with climate change and 'safe' levels of greenhouse gas emissions. The reductions in emissions envisaged by the Kyoto Protocol may not be sufficient to eliminate the risk of significant damage from climate change. In fact, it has been estimated that to mitigate, although not completely avoid climate change, current emissions should be reduced by 50 to 60% globally (IPCC, 1996).

When confronted with emission reduction targets, the question then is to what extent can reductions in CO_2 emissions be achieved efficiently, that is at a low cost. Some reductions in CO_2 emissions may even be achieved at a negative cost, as is the case of some energy efficiency measures. Also, in many cases, reductions in CO_2 emissions are likely to be accompanied by additional benefits, such as reductions in other air pollutants. Reductions in greenhouse gas emissions are technically feasible and their costs likely to be affordable, in particular if proper policies are implemented aiming at the elimination of market distortions e.g. subsidising polluting activities, and at a fiscal regime shifting the burden of taxation away from drivers of economic activity such as labour, towards unsustainable practices such as pollution.

The present study assesses the avoidance costs of biomass fuel cycles by comparing their internal costs to those of reference fossil fuel cycles and dividing the difference by the net reduction in CO_2-equivalent emissions. The avoidance costs can then be compared to estimates of damage costs to provide an indication of the 'worthiness' of the action. They can also serve as a basis for comparison with the costs of other greenhouse gas reduction options. Additional external costs and benefits e.g. reduction of local and regional pollution effects, should be accounted for when discussing avoidance costs.

3.4.5 Steps towards the internalisation of externalities

To date the internalisation of environmental externalities has been accomplished mainly through command-and-control measures, which remain the most common regulatory tool adopted for environmental protection. They mainly consist of imposing emission limits on specific activities and represent a reactive approach favouring end-of-pipe solutions and offering little flexibility. They are generally a costly solution both for the regulated and the regulator. Furthermore, emission limits being fixed, command-and-control measures offer no incentives for improvements beyond those set by the limits. Nevertheless, they may be desirable or even necessary in some cases, as for example in limiting point sources of toxic pollutants.

Issues of economic efficiency and of flexibility in achieving environmental protection and the economic burden on industry and government resulting from an increasing number of ever stricter command-and-control measures have driven an increased interest in market based mechanisms, in particular directed at certain pollutants e.g. sulphur emissions. The trend has also been assisted by an increasing economic liberalisation, increasing environmental awareness on the part of the public, improved understanding of the environmental damages of pollutants, the refining of methods to value the damages of pollution, and the greater availability of technological options to abate emissions.

A variety of economic instruments, such as taxes, subsidies, tradable permits, and also tax credits and deposit refund schemes, can be used as an alternative to command-and-control measures to meet environmental targets. Taxes and subsidies act in a similar way, the first will act by penalising a given polluting activity and the second will act by inciting cleaner activities. For example, CO_2 abatement could be achieved by introducing a CO_2 tax or by subsidising technologies which reduce emissions. In the case of taxes and subsidies, the level of the economic incentive is fixed and the market will determine the level of emissions. However, the effectiveness of the measures may vary. Tradable permits act differently. The maximum level of emissions is imposed and permits are issued accordingly. Then, following an initial distribution, the permits are traded in the market place and it is the market which will decide on their value. Economic instruments are more flexible than command-and-control measures, reduce the level of government intervention and incite enterprises to make improvements as long as there is an economic benefit. In the case of taxation based on damage cost estimates there is concern that economic benefit could cease at a level of environmental impact higher than what would be the critical level for the environment. For this reason tradable permits are often seen as an option more in tune with sustainability considerations.

For market based instruments to be most effective, they must be applied to a level playing field and, before thinking of implementing them, it may be beneficial to eliminate taxes and subsidies which bear negative effect on the environment i.e. correct government intervention failure (Roodman, 1998). Also, fiscal systems are being reviewed in many countries to shift the burden of taxation away from drivers of economic activity such as labour, towards unsustainable practices such as waste and pollution.

3.4.6 The limitations of externalities

Most of the externalities studies carried out to date acknowledge fundamental problems due to lack of scientific knowledge, uncertainties at various stages of the valuation process, biases in valuation, differences in economic assumptions and ethical issues. However, there is also general agreement that because of omissions in the quantification of impacts, the externalities presented are in most cases believed to underestimate the actual level of externalities.

There are considerable differences in the values obtained by the studies reviewed in Chapter 8. They are mainly due to: the variety of methodological approaches used; to differences in the impacts considered, in the emission estimates for the fuel cycles, in the specific damages attributed to emissions and in the assumptions underlying the risk of nuclear energy; and, where climate change is considered, to the wide range of damage estimates calculated (Lee, 1996).

Most of the earlier studies, based on top-down approaches, obtain higher externality values compared to more recent studies based on impact-pathway approaches. The extent of the effects considered is also very important. For example, the inclusion of climate change damage estimates generally leads to much higher externalities being attributed to fossil fuel cycles and has a significant influence on the nuclear cycle. The consideration of non-environmental externalities may also significantly affect the externality estimates. The technologies considered in the fuel cycle are also a cause of differences in estimates. For example, noxious emissions from a coal-based fuel cycle using integrated gasification combined cycle technology (IGCC) are much lower than those from a coal-based fuel cycle using old coal fired boilers with no emissions control. The significant differences in externality estimates are also a result of differences in generic damage estimates, in exposure-response functions and in assumptions regarding the risks associated with nuclear energy, in particular assumptions regarding probability of severe accident, releases and exposure in the case of severe accident, and risk perception.

Many of the problems affecting the reliability of externality studies can be mitigated or solved through methodological refinements and improvements in scientific knowledge. Addressing the variability of results in externality studies, the US Office of Technology Assessment (OTA) stated that "many differences can be addressed through further research and analysis. Some critical agreements over methodology, however, mask deeper disputes over values, basic policy goals, and the intended role of environmental cost studies. It is unlikely that these disputes can be resolved by technical analysis or scientific research." (OTA, 1994).

There remain, however, a number of limitations associated with externalities values which raise questions about their usefulness in decision making processes. Stirling (1997) asserts that externality valuation suffers the same drawback as other aggregated quantitative techniques, that is the "failure to address the multidimensional nature of environmental appraisal".

Some important issues concern the distribution of environmental effects. They are: the predominantly local effects of certain fuel cycles as opposed to the predominantly regional and global effects of others, the question of how to deal with intra-generational and intergenerational equity e.g. how impacts are distributed among the population and how to address long-term impacts such as climate change, and the anthropocentrism which characterises environmental valuation and which may not attribute sufficient relevance to the diversity of ecological systems.

Questions can also be raised as to the way monetary valuation addresses environmental effects in terms of severity e.g. deaths as opposed to serious injuries, immediacy e.g. injury as opposed to disease, gravity e.g. the high probability of small impacts of fossil generation as opposed to the low probability of large impacts of nuclear generation, and reversibility e.g. the irreversibility of climate change and radiation impacts as opposed to the reversibility of changes in landscape of certain renewables such as wind.

Monetary values may also give a false sense of objectivity in aggregating impacts over which those affected have different degrees of voluntariness and control e.g. the health impacts of air pollution as opposed to the right to a pristine landscape. Monetary valuation is also undermined by issues of comprehensiveness, emphasis being mainly on more readily monetisable impacts, and by issues of reliability in the techniques used in estimating impacts and monetary values, which affect the uncertainty of externalities.

These are principally due to lack of sufficient knowledge, data quality, complexity of some of the effects and diversity of empirical and theoretical models used. The variety of influences affecting the uncertainty of externalities render their treatment by orthodox probabilistic approaches a difficult task. The best way to deal with uncertainty appears to make use of ranges of values and sensitivity analysis. It is fundamental, given the current state of the valuation of external effects, to specify, at different stages of the process leading to the monetisation of the impacts, the degree of confidence in the data and models used.

3.4.7 The internalisation of externalities and sustainability

The difficulties experienced with externalities valuation have considerably hindered their application in decision and policy making. Although critical with respect to the correction of pricing mechanisms, these difficulties should be relativised when externalities are to be used as an indication of the potential costs or benefits of fuel cycles, as a measuring rod for comparing fuel cycles, and as a tool supporting rational market-based instruments aiming at the correction of market distortions. Under present circumstances externalities appear best suited as inputs for policy formulation, rather than as corrections to market prices.

In essence, the current scope of externalities of energy render them insufficient as a unique criteria, in association with private costs, on which to base decision and policy making for energy options. Other considerations, not satisfactorily addressed in terms of externalities need to be taken into account. The inability to express a variety of impacts in terms of externalities, uncertainties governing the values of those impacts which can be monetised, the risk that externalities alone will not ensure that life-supporting functions are conserved over time cause concern with regard to the achievement of sustainability. It is then fundamental to address the sustainability of fuel cycles and to consider the role of externalities in achieving sustainable energy systems.

4 Sustainability

'Sustainable development' is on the agenda of most international organisations and national and local governments, however, there is yet considerable debate on its theoretical definition and practical implications (see for example van der Hamsvoort and Latacz-Lohmann, 1998).

It is beyond the scope of this study to provide a definite framework for the assessment of the sustainability of fuel cycles. However, a discussion of the sustainability of fuel cycles is needed to address critical resource use, environmental and social issues which may be significantly affected by fuel cycles, and to address the contribution of alternative fuel cycles to sustainable development in general. The discussion of the sustainability of fuel cycles is important to provide support to decision and policy making in relation to energy supply options. Sustainable development is seen as a global objective, but its success depends on its implementation at the project level through appropriate decision and policy making.

The remainder of the discussion on sustainability in this chapter introduces a series of objectives, issues and indicators which will provide the basis for a general discussion of the sustainability of the energy systems considered in this study (see Chapter 8).

4.1 Sustainable development as an economic, environmental and social objective

Traditional development patterns and the indicators used to measure them (e.g. Gross Domestic Product) have raised doubts as to whether they will be able to guarantee sustained standards of living for the generations to come. The concept of sustainable development can be seen as a new paradigm for the development of human society. Its most recurring definition is that provided by the World Commission on Environment and Development (WCED, 1987):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

Many other definitions have been provided which illustrate various perspectives on sustainable development (see for example Pearce et al., 1989). Economists, ecologists and sociologists may have different views with regard to development (Serageldin and Steer, 1994), but it is fundamental to recognise that economic, environmental and social development are linked and that an important process of mediation is needed to achieve positive social changes.

In general terms, the key objectives of a policy aiming at sustainable development will be to:

- ensure economic development;
- stimulate the rational use of natural resources;
- preserve the ecosystem's functions;
- and enhance social well-being.

The literature often distinguishes between weak and strong sustainability, reflecting more economic or ecological approaches to sustainability. Weak sustainability assumes that man-made capital can be substituted for natural capital. Then, a situation where a capital stock consisting of man-made and natural capital is maintained constant could be considered as sustainable. Strong sustainability assumes that the ecosystem possesses fundamental life-sustaining functions which cannot be substituted by man-made capital. An example of such life-sustaining function is that operated by the ozone layer.

The concept of sustainable development is very broad and further discussion will focus on the issues relevant to sustainable energy supply, bearing in mind the general features discussed above.

4.2 Issues concerning sustainable energy supply

The present study focuses on economic and environmental aspects of sustainable development. They are, however, inevitably linked to social considerations, since changes in economic and environmental aspects and trade-offs between them will influence social issues such as employment and intra- and inter-generational equity.

Economic considerations are fundamental to sustainable development. The services provided by energy are a key driver of development and so is the availability of energy at a low social cost. Also, foreign exchange impacts of energy and energy security issues are of concern with regard to sustainable development. The first are a serious barrier to the economic development of many countries and the second pose serious concern to global economic stability.

Energy is a cornerstone of economic and social development. However, energy generation and its use in the residential, commercial, industrial and transport sectors has severe consequences on the local, regional and global environment. Smog, acidification and climate change are some of the environmental concerns associated with energy related activities. All these and more translate to external costs which are generally not accounted for when choosing amongst different energy supply and end-use options. However, as discussed above there are limitations to external costs and to the extent these can be used to ensure sustainability (weak vs. strong sustainability). The contribution of fuel cycles to strong sustainability needs to be discussed in addition to their contribution to weak sustainability.

Sustainable energy strategies may in many cases bring about social improvements such as indigenous capacity building, jobs, poverty alleviation and rural development in general.

There are a variety of energy supply options which could potentially contribute to a global sustainable energy supply. However, there are a series of obstacles in the move to a more sustainable energy supply.

Flavin and Lenssen (1994) indicate a series of key elements for simultaneously meeting the economic and environmental needs of the electricity supply industry. They are:

- a competitive market for wholesale electricity generation;
- an open access transmission system;
- incentives for reliance on diverse power sources, taking into consideration the environmental differences among them;
- and development of a service- rather than commodity-oriented local distribution system committed to integrated resource planning and demand-side management.

Sustainable energy supply will have to evolve in a political and economic environment characterised by: globalisation, liberalisation, a changing role of government, fiscal austerity and increasing public participation.

The fuel cycles will be discussed with regard to the above considerations and in relation to a series of indicators based on economic and environmental themes relevant to decision and policy making.

4.3 Measuring the sustainability of energy supply

Economic, environmental and social indicators, should ideally provide a measure of sustainable development and send signals for changes in policy and practice. To define appropriate indicators is not an easy task, no less than to create a consensus over defined indicators. Also the question arises how to assess sustainable development when the trade-offs between economic, environmental and social objectives will cause some indicators to increase and others to decrease. This is where decision-making tools and political judgement are crucial.

The following sections wish to broadly define a series of indicators which could be considered in assessing the sustainability of energy supply and which will be used as a basis for discussion of the fuel cycles considered in this study. A discussion on the sustainability of fuel cycles will address monetary and non-monetary indicators of sustainability.

4.3.1 Monetary indicators

One way of evaluating the contribution to sustainable development of alternative means of providing goods and services is by comparing the social costs and benefits incurred by the alternatives. The general rule would be to choose the alternative yielding the minimum social costs or maximum social benefits as the one contributing the most to sustainable development.

The principal monetary indicator to be discussed with regard to the sustainability of fuel cycles is then social cost. However, both its components, private and external costs, need particular consideration.

Private costs are of significance especially for novel fuel cycles with considerable potential for cost reductions. The influence of the private costs on the overall economic efficiency, expressed in terms of social costs, is significant and needs to be properly addressed. A particular fuel cycle may have environmental and social benefits, but if its private costs are high it is likely to remain less sustainable, in terms of weak sustainability, compared to a system with significantly lower private costs. Ways of reducing the private costs of promising sustainable energy technologies are imperative.

Also, private costs may provide an indicator of costs which may be incurred to avoid environmental impacts and to meet strong sustainability criteria (see next section).

External costs provide an indicator of the unaccounted economic burden on society from the supply its energy needs. They complement the private costs in indicating the economic efficiency and sustainability (weak) of a fuel cycle. Hence, the importance of their internalisation.

Social costs do not allow to determine whether fuel cycles are sustainable or not in terms of strong sustainability, but allow to compare options and select those which may contribute to a more sustainable energy supply.

Monetary indicators can be applied at a project level, but are also of interest in discussing the costs to society of different energy scenarios and policies at a regional level. In this respect, consideration of monetary indicators may also indicate a more sustainable path for energy supply.

Reducing the social costs of energy supply would represent a move towards achieving weak sustainability, and contribute to strong sustainability without ensuring it. Issues related to valuation techniques e.g. impact determination and monetary valuation, and the uncertainty over the ability of weak sustainability to guarantee the safeguard of life-sustaining and social functions (strong sustainability) press for the consideration of a series of non-monetary indicators.

An overall efficient and equitable use of resources should aim at the minimisation of the social costs of the system within the limits imposed by strong sustainability constraints[8].

4.3.2 Non-monetary indicators

Non-monetary indicators should be used to address environmental and social issues of concern. A series of indicators are defined below which will be used to discuss the fuel cycles considered in this study.

[8] It is important to note that both misleading external costs and strong sustainability criteria could lead to serious misallocation of resources

Based on key principles of sustainable development and on potential impacts of fuel cycles, non-monetary indicators should focus on:

- the efficient use of non-renewable resources and substitution by renewable resources;
- the emission of natural and man-made substances to air, soil and water resulting in potentially significant impacts;
- the conservation of the ecosystem's services;
- and the fulfilment of human needs.

The above considerations can be used to define *ecological* and *socio-economic indicators*. These indicators should be important in assessing the long-term sustainability of fuel cycles at local, regional and global scale, and should provide constraints within which decision and policy making should work towards optimal solutions.

<u>Ecological indicators</u>

Ecological indicators should be defined for all *significant* impacts, within the ecological impact categories defined in Table 1, which result from the fuel cycles activities. The ecological impacts categories listed are found in the framework proposals for sustainable development indicators of institutions such as the OECD.

Ecological indicators can be of two types:

- Environmental pressure indicators (EPI); and
- Ecosystem function indicators (EFI).

Environmental pressure indicators (EPI)

Natural and man-made substances will be released to the ecosphere as a result of the fuel cycle activities. EPIs should then be defined for all *significant* impacts which result from emissions to air, soil and water from the fuel cycles considered. These indicators will need to consider the spatial and temporal dependency of the environmental pressures considered.

Effect scores can be used to relate type and quantity of pollutants emitted to different significant impacts. Different pollutants contributing to a single impact can be aggregated and expressed as a single effect score consisting of an equivalent emission of one of the pollutants contributing to the impact e.g. greenhouse gases can be expressed as CO_2 equivalents and acidifying agents can be expressed as NO_2 equivalents.

Effect scores are not meaningful enough to be used as indicators, but they are useful in comparing the relative contribution to sustainability of alternative systems. A meaningful EPI could be obtained via a normalisation step which would relate the effect score to a constraint or target. For example, normalisation factors could be based on per capita emission targets for CO_2 and on critical levels for acidifying substances.

Ecosystem function indicators (EFI)

Biomass fuel cycles may affect ecosystem functions in many ways. Impacts resulting from soil erosion, nutrient variation in soils, groundwater use, and other impacts which can result from large-scale transformation of land may require consideration.

Effect scores could be provided as soil erosion rates, nutrient levels and groundwater use for the biomass fuel cycles. These can then be normalised by target or constraint values to provide EFIs.

Possible effects of large-scale transformations of land should be assessed when considering large-scale, long-term implementation of biomass fuel cycles. Also, for biomass fuel cycles based on current agricultural production e.g. sugarcane plantations in Brazil, the sustainability of the present land use should be discussed.

Socio-economic indicators

Two types of socio-economic indicators may be considered:

- Resource use indicators (RUI); and
- Human resources indicators (HRI).

Resource use indicators (RUI)

With regard to energy supply, resource use indicators will focus on non-renewable energy use. The effect score for resource use can then be expressed as the non-renewable energy consumed by fuel cycles. The RUI could then be obtained by relating the effect score to an imposed rate of non-renewable energy substitution by renewable energies or efficiency measures which would account for their finite nature.

Human resources indicators (HRI)

It may be of interest to provide an indication of the labour requirement and conditions of fuel cycles. The effects of the fuel cycles on labour should be discussed in relation to issues such as its conditions and geographical distribution.

5 Decision and policy analysis

The decision and policy analysis will draw on the regional context, on the economic, environmental and resource use analysis and on the sustainability analysis to discuss biomass fuel cycle requirements, opportunities and barriers, especially in relation to reference energy systems. The discussion of biomass fuel cycle requirements, opportunities and barriers in turn will form the basis for a discussion on decision and policy making and on the possible influence of policy measures on decision making.

CHAPTER 3

Biomass Gasification for Heat and Electricity Generation

1 Introduction

Gasification is a thermochemical process which has been exploited for over a century for converting solid feedstocks to gaseous energy carriers. The first gasifier patent was issued in England toward the end of the 18th century and producer gas from coal was mainly used as lighting fuel throughout the 19th century. With the turn of the 20th century the main use of producer gas, obtained essentially from coal, switched to electricity generation and automotive applications via internal combustion engines. The use of producer gas was then gradually supplanted by the use of higher energy density liquid fuels and as a result confined to areas with expensive or unreliable supplies of petroleum fuels. Efforts in gasification technology research have however persisted, driven mainly by the need for cleaner and more efficient electricity generation technologies based on coal. In the last decade biomass and municipal solid waste gasification have attracted increasing interest.

Biomass gasification allows the conversion of different biomass feedstocks to a more convenient gaseous fuel which can then be used in conventional equipment (e.g. boilers, engines, turbines) for the generation of heat and electricity. The conversion to a gaseous fuel provides a wider choice of technologies for heat and electricity generation for small to large scale applications. Furthermore, energy generation from gaseous fuels is likely to be more efficient compared to the direct combustion of solid fuels. High efficiency is a particularly important issue for larger scale biomass systems because of the possible transport implications of low energy density biomass fuels. The upgrading of biomass feedstocks to gaseous fuels is also likely to lead to a cleaner conversion.

The coupling of biomass gasification with gas and steam turbines can provide a modern, efficient and clean biomass system for the generation of heat and electricity in industry, in particular the power supply industry. Biomass integrated gasification combined cycle

(BIG/CC) systems are currently at the demonstration stage and their market penetration will depend on a number of factors:

- successful demonstration of the technology;
- economic competitiveness with other energy conversion technologies and fuel cycles;
- environmental performance of the biomass fuel cycle as well as the influence of environmental factors on decision making;
- and increasingly on other socio-economic factors e.g. energy security, contribution to national balance of payments, creation of jobs requiring qualified labour, export potential of the technology.

The present chapter provides an overview of the state-of-the-art of biomass gasification for heat and electricity generation.

2 Fundamentals of gasification

Thermochemical processing of biomass yields gaseous, liquid and solid products and offers a means of producing useful gaseous and/or liquid fuels. Gasification is a total degradation process consisting of a sequence of thermal and thermochemical processes which converts practically all the carbon in the biomass to gaseous form, leaving an inert residue. The gas produced consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2) (if air is used as the oxidising agent) and contains impurities such as small char particles, ash, tars and oils. The solid residue will consist of ash (composed principally of the oxides of Ca, K, Na, Mg and Si) and possibly carbon or char. Biomass ash has a melting point situated around 1000°C, thus it is important to keep the operating temperature below this figure to avoid ash sintering and slagging. At temperatures above 1300°C the ash is likely to melt and could be removed as a liquid.

The following sequence of phenomena is typical of all gasifiers: drying, heating, thermal decomposition (combustion and pyrolysis), gasification. Table 3 illustrates the reactions occurring in gasifiers. In directly heated gasifiers the energy (heat) necessary for the endothermic reactions is provided by combustion and partial combustion reactions within the gasifier. In indirectly heated gasifiers, the heat is generated outside the gasifier and then exchanged with the gasifier. Gasifiers can operate at low (near-atmospheric) or high (several atmospheres) pressure.

Table 3: Reactions occurring in gasifiers (Hedley and Bustani, 1989)

Reactions	Enthalpy of reaction (kJ/mol)
Heterogeneous reactions	
Combustion	
$C + ½O_2 = CO$	-123.1
$C + O_2 = CO_2$	-405.9
Pyrolysis	
$4C_nH_m = mCH_4 + (4n - m)C$	exothermic
Gasification	
$C + CO_2 = 2CO$ (Badouard)	159.7
$C + H_2O = CO + H_2$ (Steam-carbon)	118.7
$C + 2H_2 = CH_4$ (Hydrogasification)	-87.4
Homogeneous reactions	
Gas phase reactions	
$CO + H_2O = CO_2 + H_2$ (Water-gas shift)	-40.9
$CO + 3H_2 = CH_4 + H_2O$ (Methanisation)	-206.3

The Badouard, the steam-carbon and the methanisation reactions are favoured with increasing temperature and decreasing pressure; the hydrogasification reaction is favoured with decreasing temperature and increasing pressure; the water-gas shift reaction is favoured at low temperatures but is independent of pressure. Temperature and pressure operating conditions as well as residence time are therefore key factors in determining the nature of the product gas. Data from existing gasifiers shows that the heating value of the product gas varies little between pressurised and atmospheric gasification for similar operating temperatures (Bridgwater and Evans, 1993). Gas quality is usually measured in terms of CO and H_2 quantity and ratio.

2.1 Effect of feedstock properties

Water vapour is an essential component of the gasification reactions. However, a high moisture content of the feedstock has an adverse effect on the thermal balance and influences the gas yield, composition and heating value. A low ash content improves the thermal balance, reduces the occlusion and loss of carbon in the residue and reduces operating problems due to sintering and slagging. Sintering and slagging will depend on the gasifier temperature and, in the case of biomass, are likely to be related to the presence of SiO_2 which possesses the lowest melting point among the ash components. The fuel particles size will affect the rate of heat and mass transfer in the gasifier. Elements such as sulphur (S) and chlorine (Cl) lead to the formation of corrosive gas components such as H_2S and HCl. Alkali metals are also a major concern with regard to corrosion especially when combined with sulphur. Nitrogen (N) in the feedstock leads to the formation of ammonia (NH_3) which can act as a major source of NO_x emissions when combusted in engines or gas turbines.

2.2 Effect of operating parameters

The operating temperature will determine the equilibrium composition of the gas. High operating temperatures increase to different extents the intrinsic rate of all chemical and physical phenomena and result in leaner gases. Gasifier temperatures should be sufficiently high to produce non-condensable tars, in order to avoid problems in downstream conversion equipment. Condensable tars are to be avoided if the product gas is to be used in engine or gas turbine applications and they will have to be cracked or removed prior to the operation of engines or gas turbines. Exceedingly high temperatures (>1000°C) may lead to ash sintering and slagging. High operating pressures increase the absolute rate of reaction, the heat and mass transfer, and shift the gas equilibrium composition in favour of CH_4 and CO_2. The air factor (air flow rate into the gasifier) is a key regulating parameter of a fluidised bed gasifier using air as the gasifying agent. Excessive air factors lead to low heating values (nitrogen dilution and excessive combustion). Insufficient air factors lead to low reactor temperatures and low rates of gasification.

3 Gasification and gasifier types

Three main types of gasification can be distinguished based on the gasifying agent and the way in which the heat for the gasification reactions is provided: directly heated air gasification, directly heated oxygen gasification and indirectly heated gasification.

In the first two cases the injected gasifying agent burns part of the feedstock to provide the heat necessary to gasify the remainder of the feed in an air poor environment. Air gasification leads to a product gas rich in nitrogen (50-65%) and consequently low in calorific value (4-8 MJ/Nm^3). Small-scale gasifiers are usually of the air gasification type, but air gasification may also be the choice for larger scale gasification e.g. the TPS (Pitcher et al., 1998) and Bioflow (Ståhl and Neergard, 1998) systems discussed in Chapter 4. Oxygen gasification requires an oxygen producing plant which increases costs and energy consumption, but leads to a producer gas low in nitrogen content and of medium calorific value (10-18 MJ/Nm^3). Steam can be added to both air and oxygen gasification processes to act as a thermal moderator and as a reagent in the gasification process, and enhances the calorific value of the gas. Oxygen and steam gasification are not required for biomass gasification, but are used for the gasification of less reactive fuels such as coal.

Indirectly heated gasifiers do not require air or oxygen input, the heat necessary for gasification being generated outside the gasifier. For example, the bed material can be heated in a separate reactor by burning the char from the gasifier as in the Battelle process or the heat can be generated by pulse burners and transferred by in-bed tubes as in the MTCI process (Bridgwater and Evans, 1993). Indirectly heated gasifiers produce a medium calorific value gas, and steam can be input to the gasifier in order to favour the gasification reaction.

Gasifier design influences the gaseous product with respect to gas composition, condensed liquids, suspended solids and water content. A number of reactor types are available: fixed bed, fluidised bed, circulating fluidised bed, entrained flow, molten bath. There are several examples of small scale fixed bed biomass gasification applications around the world (Stassen, 1995 and Wilen and Kurkela, 1997). The gasification systems considered in this study are of the circulating fluidised bed (CFB) type, since CFB gasification technology appears as the most suitable for integration with power generation systems of capacities greater than 10 MW_e. Biomass integrated gasification (BIG) systems for power generation based on CFB gasification are currently at the demonstration stage.

Two CFB gasification-based systems can be distinguished according to their operating pressure: near-atmospheric or low-pressure (LP) and high-pressure (HP) systems. Systems based on atmospheric pressure gasification can be coupled to wet gas scrubbing for gas clean-up, and appear promising because of the technologically and commercially proven nature of the various components. However, large-scale (>10 MW_e) operation integrated with power generation equipment has yet to be proven, and demonstration plants are to be commissioned within the next years e.g. in the UK and Brazil (Pitcher et al., 1998; Waldheim and Carpentieri, 1998). Systems based on pressurised gasification are more suitable for use with hot gas filtration for gas clean-up, but present a more complex operation and higher degree of system control. The technical performance of some of the components of the system is still at the testing stage e.g. hot gas cleaning. Again, large-scale operation integrated with power generation components has yet to be proven. The Värnamo demonstration plant in Sweden (Sydkraft, 1998), which uses high pressure gasification, is the only example of BIG plant with operational experience coupled to a gas turbine.

4 Activities characteristic of biomass integrated gasification systems for heat and electricity generation

This section considers activities typical of large-scale systems. The conversion of biomass to heat and electricity via gasification involves, in general, the following steps: biomass storage, on-site biomass transfer, size reduction, drying, feeding, gasification, fuel gas cleaning and cooling, power generation, flue gas cleaning, and ash disposal or recycling.

4.1 Storage, transfer and pre-treatment of the feedstock

4.1.1 Storage

Biomass storage is required to ensure the continuous operation of the facility. To limit the space required for storage at the plant site, biomass must be stored in relatively high piles. Two main problems associated to fuel storage are decomposition and self-heating. Self-heating increases the rate of decomposition and fire risk, and it encourages the growth of thermophilic fungi whose spores can cause a respiratory condition in humans similar to 'farmers lung'. Some small biomass losses may occur at the storage stage but they are likely to be negligible. Intermediary storage of the fuel between the pre-treatment and gasification stage usually occurs in storage silos. The material flow characteristics of the stored biomass need to be considered in the design of the intermediary storage system in order to avoid flow problems.

4.1.2 On-site biomass transfer

On-site biomass transfer occurs between storage facilities, pre-treatment equipment and gasification equipment. Such transport technology is readily available and modern type enclosed conveyor belt systems are likely to be used.

4.1.3 Size control

Biomass particle size affects gasification reaction rates and gas composition. Since size control operations are expensive and energy intensive, there is a trade-off, in terms of cost and energy, between particle size reduction and reactor design, and the yield and characteristics of the product gas. In practical terms, the size of the feedstock particles is dependent on the biomass requirements imposed by the adopted gasification system.

In the case of CFB gasifiers, the size of the chips fed to the gasifier is likely to be between 2 cm and 5 cm, and size reduction is likely to be achieved by means of crushers. Also, size reduction makes the drying, transfer and intermediate storage of the biomass easier.

4.1.4 Drying

The moisture content of the feedstock affects the gas composition and the energy balance of the process, gasification being an endothermic process. Water vapour is, however, an essential component of the gasification reactions. There is therefore a trade-off between the extent of fuel drying and the quality of product gas. Drying of the feedstock to a moisture content of about 15% is commonly adopted.

Fuel drying is likely to be the most energy intensive activity in the gasification process. Important contributions can be made to the energy balance by, for example, using flue gases or steam to dry the biomass. The heat used for drying does not have to be high temperature, and a low temperature level is actually desired as it will prevent the evaporation of undesirable organic components. Direct heating systems, where the heating medium (e.g. flue gas) is in direct contact with the fuel to be dried, using a rotary drum or fluidised bed type are likely to be adopted. The systems are also likely to be open, meaning that the heating medium is then discharged to the atmosphere.

Drying activities will result in dust emissions. In most cases a simple baghouse filter will be employed to satisfactorily reduce dust emissions. However, in the case of a large drying facility, considerable quantities of water vapour (likely to contain significant quantities of organic compounds) could result in addition to dust. A wet gas scrubber followed by a flue gas condensation system may then be used to clean the flue gas (mainly of dust and organic compounds such as terpenes) and recover the heat from the water vapour present in the flue gas. The condensed water requires a biological treatment before it can be discharged to the sewage system. Condensed organic compounds from the fuel drying activity possess a fuel value and hence the energy can be recovered from their combustion. Particular care is required in the design of drying installations to avoid fire and explosion risks.

4.2 Feeding the biomass

The feeding of biomass into gasifiers has proved to be problematic, and it tends to be costly and energy intensive. Physical properties of the biomass, such as its size and density, affect the performance of feeding systems. Also, the choice of a feeder will depend mainly on the pressure against which it has to operate. The feeding systems discussed in this section apply to atmospheric and pressurised circulating fluidised bed gasifiers.

A screw feeder, where the screw forms a compact, pressure-retaining plug from the feedstock in the feed channel, is suitable for atmospheric gasifiers. For pressurised gasifiers a lock-hopper feeder or a lock-hopper/screw-piston feeder is required. The lock-hopper feeder uses a screw feeder, but is more complex than a simple screw feeder because of the need of pressurising the feedstock prior to its input into the gasifier. Pressurisation of the feedstock is generally achieved using lock-hopper devices which require large quantities of inert gases (e.g. liquid nitrogen). The lock-hopper/screw-piston feeder allows a considerable reduction in inert gas consumption by the introduction of pneumatic feeding (Piervik and Curvers, 1995). Particular care is required in the design of feeding systems to limit blockages, as well as fire and explosion risks.

4.3 Circulating fluidised bed gasification

Air-blown circulating fluidised bed gasifiers are of interest because they produce a good quality LCV gas (4-6MJ/Nm^3) and possess a very high carbon conversion efficiency, while allowing high capacity, good tolerance to variations in fuel quality and reliable operation. The high and homogeneously distributed temperatures and the use of particular bed materials, such as dolomite, favour tar cracking. Successful tar cracking can also be achieved using secondary circulating fluidised bed reactors as will be the case in the ARBRE plant. Also, successful tests on catalytic tar cracking have been performed, for example, by introducing nickel compounds into the gasifier. Sulphur control is made easier because of the significant reduction that can be achieved by adding limestone or dolomite to the gasifier bed. However, biomass feedstocks are not likely to require sulphur control because of their very low sulphur content. Sulphur levels will, nevertheless, have to be lower than those imposed by turbine requirements which are provided in Table 4. The high fluid velocity entrains large amounts of solids with the product gas which are recycled back to the gasifier via the cyclones to improve conversion efficiency. Carbon conversion efficiencies for circulating fluidised bed gasifiers are about 98%.

A fluidised bed gasifier consists of a plenum chamber surmounted by a gas distributor, a refractory lined steel shell enclosing the granular bed and the freeboard zone, and a feeding device. The bed material is a clean and graded fraction of heat resistant material, generally sand, alumina, limestone, dolomite or fly ash. It is fluidised by the upward stream of the gasifying agent rising in the form of bubbles and the continuous motion causes an excellent mixing of the solids and results in a uniform temperature distribution. High superficial velocities of the gas cause elutriation of solid particles leading to a circulating bed design.

The gas composition and heating values do not differ significantly between pressurised and atmospheric operation for similar operating temperatures. The low calorific value gas (4-6 MJ/Nm^3) will consist mainly of inert nitrogen and carbon dioxide gases and of the combustible gases carbon monoxide, hydrogen and methane. Contaminant concentrations e.g. sulphur, chlorine, alkali and heavy metals, will depend on the quality and composition of the biomass and on the bed material used.

Pressurised gasifiers imply a more complex and costly feeding system (i.e. lock hopper feeder and inert gas) compared to near-atmospheric gasifiers. Also, pressurised systems require a higher degree of process control. However, when the product gas is used for power generation in a gas turbine, pressurised gasifiers considerably reduce the fuel gas compression requirements. Pressurisation is obtained by compressing the gasifying air using the turbine compressor. This results in the compression of a much lower volume of air compared to the fuel gas volume which would otherwise have to be compressed prior to combustion in the gas turbine. Also, in pressurised gasification systems using hot gas clean-up equipment, tars will have less chances of condensing and causing damage to equipment and need not be removed from the gas, which allows to making use of the energy content of tars present in the product gas.

Pressurised gasification systems can achieve net efficiencies at the gas turbine inlet of 92-95% relative to the calorific value of the biomass input, with 5-8% energy losses attributable to heat losses to the environment, to the provision of inert gas to the lock-hoppers and to the compression of the air input to the gasifier. Atmospheric gasification system efficiencies are lower, between 80-85%, due to the higher energy input associated with the wet gas cleaning and with the fuel gas compression (Bridgwater, 1995). On this basis, electricity generation based on pressurised gasification could be 4-8% more efficient than atmospheric gasification systems. However, simulation of electricity generation from pressurised or near-atmospheric pressure systems indicate differences in efficiencies between the systems of about 3% (Consonni and Larson, 1996) If hot gas clean-up systems prove successful their use is also envisaged with atmospheric gasifiers, thus reducing the energy consumption associated with gas cleaning.

4.4 Fuel gas cleaning

The fuel gas contains a series of impurities e.g. organic compounds, alkali metals, ammonia, char, ash. These need to be removed to varying degrees depending on the downstream conversion process and on potential environmental impacts.

After leaving the gasifier, the fuel gas goes through a series of cyclones, which remove the bulk of the dust present in the gas. Then in the TPS atmospheric system design it goes through a tar cracking device similar to the gasifier, before proceeding to a gas cooling device. In the case of a pressurised system, the gas goes from the gasifier directly to the gas cooling device. The gas is then cleaned to meet gas turbine requirements in a wet gas scrubber or hot gas filter. Physical filtration, in the form of hot gas filtration systems using ceramic or sintered metal filters, is likely to offer a simpler and less costly option than wet gas scrubbing. It also considerably reduces the water consumption and liquid effluents of the plant. However, unlike gas scrubbing, hot gas filtration systems are not a fully demonstrated and commercial technology. The removal of some polluting e.g. nitrogen, and corrosive e.g. chlorine, compounds and of excessive water vapour from the product gas may be problematic when using hot gas filters. However, testing and demonstration currently underway appear to indicate that environmental and gas turbine fuel requirements can be met with hot gas filtration systems (Sydkraft, 1998). These results are very much fuel dependent. Hot gas cleaning does not remove ammonia from the gas stream, which is instead washed out in a wet gas scrubbing system, and high fuel bound NO_x emissions could result if other means for reducing ammonia levels are not adopted e.g. catalytic bed material. Issues such as filter blocking, cleaning and lifetime are also being addressed. The Värnamo Power Plant is the only example of hot gas cleaning system coupled to a gas turbine with operational experience.

4.5 Heat and electricity generation

The product gas can be burned in boilers to generate heat or raise steam, in internal combustion engines to generate electricity and heat at small to medium scale (from a few kilowatts to a few megawatts), and in gas turbines to generate electricity (Brayton cycle) and heat at small to large scale. In large scale systems using gas turbines, the exhaust gas from the gas turbine can be used to raise steam in a heat recovery steam generator (HRSG) for generating additional electricity using a steam turbine (Rankine cycle), leading to combined cycle operation. In a combined heat and power plant, designed for district heating, the flue gas from the combustion of the product gas goes through a heat exchange system to raise the temperature of a heat transport fluid, generally water, circulating in a district heating system. Residual heat in the flue gas can be used to dry the biomass, prior to its discharge to the atmosphere.

Factors such as capacity, technical performance, capital costs, efficiencies and emissions will determine the preferred generating technology. Also, the relative demand for heat and electricity will influence the technology choice.

4.5.1 Combustion in engines

Engines require input of a clean gas to minimise engine wear, to avoid tar deposition and to reduce coking in the engine, particularly in the valve area. The gas temperature should be as low as possible to inject a maximum amount of energy into the cylinders.

Engines have the advantage that they can be run on a variety of fuels or fuel combinations with relatively minor adjustments. Gas engines for power generation are commercially available for small to large scale applications (from tens of kilowatts to tens of megawatts). Their efficiencies are estimated to range between 25 and 40% depending on the capacity.

There is considerable experience with coupling boilers and engines to gasifiers at small to medium scale (<10 MW_e) (Stassen, 1995 and Wilen and Kurkela, 1997). The provision of a fuel gas of suitable quality is the major problem leading to frequent maintenance and shortened engine lifetimes. Engines are commercially available, there is much experience with running engines on a wide variety of gases and they are generally more tolerable to contaminants than turbines. However, turbines hold promise of higher efficiencies (especially at scales allowing for combined cycle operation), lower costs and cleaner operation. Also, turbines are likely to be more suited to combined heat and power application because of higher grade heat generation compared to engines.

4.5.2 Combustion in gas turbines

Gas turbines cover a wide range of electrical capacities ranging from a few hundred kilowatts to tens of megawatts, with recent developments in microturbines of a few tens to a few hundred kilowatts capacity (see for example Prabhu and Tiangco, 1999). Gas turbines have more stringent fuel requirements but are likely to possess higher efficiency and lower emissions compared to reciprocating engines. Fuel gas specifications for operation in gas turbines are very stringent, and will imply a careful consideration of the quality and composition of the feedstock, the gasification process and the gas cleaning system used. The main areas of concern are: the contamination of the fuel gas by alkali metals, tars, sulphur, chlorine, particulates and other trace elements; the fuel gas heating value and therefore its composition and volume; the flame properties of the gas within the combustion chamber; and the presence in the fuel gas of fuel bound nitrogen leading to NO_x formation during combustion. The minimum allowable gas heating value depends on turbine design (heating value affects air-to-fuel ratio and therefore affects the inlet requirements based on total mass flow). The strict gas specifications result in low emission levels for most pollutants.

The following factors contribute to achieving gas turbine fuel requirements:

1. Biomass feedstock properties:

- low (10-15%) moisture content so as not to hamper efficient gasification process and adversely affect the gas heating value;
- low ash feedstock to reduce filtering demand and potential slagging;
- low alkalinity feedstock to reduce fouling.

2. Gasification process:

- choice of gasifying agent (air, oxygen or steam) influences heating value and can also reduce or eliminate formation of problem tars;
- choice of gasifier type influences carry-over of particulates;
- higher operating temperatures vaporise alkali metals which must be condensed and filtered out e.g. vaporisation occurs in CFBs (900-1100°C), but not in bubbling fluidised beds (600-800°C), and tars are also vaporised and cracked to a certain extent e.g. CFBs crack more tar compounds than bubbling fluidised beds.

3. Gas cooling and cleaning system:

- special bed materials e.g. dolomite, and catalysts in the gasifier or in a separate reactor can be used for sulphur and chlorine removal to avoid the formation of ammonia and for tar cracking;
- gas cooling is necessary to protect gas turbine components from heat damage and the degree of cooling will depend on the gas cleaning technique adopted e.g. hot gas filter or wet gas scrubbing;
- hot gas filter systems remove particulates and alkali metals;
- tars may not need be removed from the gas if the temperature remains higher than the gas condensation temperature;
- wet gas scrubbing removes most fuel gas contaminants (ammonia is not removed by hot gas filters but can be washed out of the gas by an acidic solution in a wet gas scrubber).

Pressurised gasifiers are well suited for hot gas clean up (below 600°C) prior to direct combustion in the turbine. At temperatures below 600°C alkali metals precipitate onto the particulates present in the gas and are removed by the gas cleaning system. Tar cracking is not required for pressurised gasification systems because of the elevated gas temperature (the tars are likely to be in non-condensable form). In the case of hot gas cleaning, fuel bound nitrogen, in the form of ammonia, may cause concern over NO_x emissions since about 60% of the ammonia in the fuel could be converted to NO_x during combustion. Atmospheric gasifiers generally require tar cracking or removal, cool (<200°C) gas cleaning and compression of the gas prior to turbine combustion. Hot gas filtration methods are being tested for atmospheric gasifiers.

Experience with gas turbines fuelled with low calorific value gas has been limited in the past, some models being operated on blast furnace gas. Interest in biomass and waste gasification has stimulated turbine development from manufacturers such as GEC Alsthom and General Electric. Also, a number of companies (e.g. Allied Signal, Westinghouse and Capstone) have become active in the development of microturbines e.g. of a capacity of 100 kW. Requirements vary considerably between turbine models. An indication of gas turbine fuel requirements is given in Table 4. Table 5 provides an indicative comparison of fuel gas requirements for different applications.

Table 4: Notional gas turbine fuel specifications (Bridgwater, 1995; Brown and van den Heuvel, 1996; Cannon, 1997)

Gas heating value (LHV, MJ/Nm^3)	4 - 6
Gas inlet temperature (°C)	<425
Gas hydrogen content (vol. %)	10 - 20
Alkali metals (Na + K) (ppmw)	<0.1
H_2S (ppmv)	<100
HCl (ppmw)	<0.5
Naphthalene and tars (ppmv)	<100
Particulates (99% below 10μm) (ppmw)	<1
Vanadium (ppmw)	<0.1
Combinations: Alkali metals + sulfur (H_2S) (ppmw)	<0.1

Care must be taken that the fuel gas is supplied to the turbine at a temperature greater than the gas dew point temperature in order to avoid droplet formation. Also, the fuel gas must be unsaturated with water to avoid the formation of acids which could result mainly from the presence of H_2S and CO_2.

Table 5: Product gas requirements

Application	Fuel gas temperature	Maximum particulates	Maximum tars	Contaminants
Boilers	High to use sensible heat	Low - moderate	Moderate	Low - moderate
Engine	As low as possible	Very low	Very low	Low
Turbine	As high as possible	None	None	None - low

Thermal NO_x formation for low calorific value gas combustion in the GEC Alsthom EGT Typhoon turbine is very low, less than 10 ppmv (Cannon, 1997), in particular when compared with emissions from natural gas fired turbines where low NO_x burners currently achieve emissions of about 25 ppmv (Collins, 1994). The low emissions result from the lower combustion temperature and from a leaner combustion.

Combined cycle operation

Single cycle efficiencies of about 36% and combined cycle efficiencies of 47% or higher (up to about 52%) are typical of present day natural gas fuelled plants. BIG/GT single or combined cycle efficiencies, relative to the energy content of the fuel input, will not match the efficiencies of gas turbines fuelled on natural gas because combustion temperatures are lower and because part of the energy content in the biomass fuel will be dissipated in the production of the fuel gas. Table 6 shows notional gas and steam turbine generating efficiencies.

Table 6: Notional generating equipment efficiencies

Equipment	Efficiency
GT running on NG	36%
GT running on LCV gas	31%
ST generating system (>100 MW_e)	35%
ST generating system (<100 MW_e)	25%
ST generating system (typical for small scale)	15-20%

GT: gas turbine; NG: natural gas; LCV: low calorific value; ST: steam turbine

It is possible to estimate the overall efficiency of the BIG/CC system using the above efficiencies and the efficiency of the gasification system up to the gas turbine inlet discussed in Section 4.3. The following electrical efficiencies are estimated to be attainable for BIG/CC plants (Table 7).

Table 7: Notional BIG/CC electrical efficiencies

	Capacity <100 MW_e	Capacity >100 MW_e
Atmospheric system	43%	50%
Pressurised system	46%	53%

A number of BIG/CC demonstration plants are planned in Europe, the US and Brazil. Details on the demonstration plants can be found in Beenackers and Maniatis (1997).

4.5.3 Comparison with biomass direct combustion

Gasification presents a series of advantages over combustion, in particular at scales typical of biomass to energy systems. Engines and gas turbines, especially in combined cycle operation, will generally possess higher electrical conversion efficiencies compared to steam cycles. At small scale, steam turbines possess lower efficiencies compared to engines and gas turbines, and at a larger scale, gasification offers the possibility of combined cycle operation. In combined heat and power operation gas turbine systems will generally be characterised by higher power to heat ratios leading to a greater product value in most applications.

Gasification based systems are likely to be less affected by diseconomies of scale at the relatively small scales typical of biomass energy. For the larger scale applications, CFB gasifiers and CFB combustion units appear to be comparable with respect to specific capital and operating costs, efficiency, extent of automation and controllability of process. Although the capital cost of a gasifier unit should be lower than the equivalent combustion unit because of its substantially reduced volume, gasifier systems require additional control and safety features which counteract such a cost advantage. Steam turbine systems are characterised by important economies of scale compared to gas turbine systems, making gas turbines a more likely viable option.

However, combustion possesses a more advanced technological and commercial status, accompanied by greater equipment availability, reliability and expertise.

4.5.4 Comparison with coal gasification

Coal presents a series of advantages and disadvantages with respect to biomass. On one hand it is easier and less costly to handle and process, it is easier to feed, particularly in pressurised systems, and it may require less complex supply logistics. On the other hand coal has a much lower level of volatiles than biomass (typically 30% compared to over 70% for biomass), its char is significantly less reactive than biomass char implying greater reactor sizes, residence times and the use of oxygen as a gasifying agent, it possesses a higher ash content than biomass (the processing of which is also more complex due to higher contamination levels), and it often contains significant quantities of sulphur requiring more complex and costly gas cleaning systems. Coal also has a major environmental disadvantage with respect to biomass in that it results in large CO_2 emissions, contributing to global warming.

4.6 Waste disposal

Waste water and solid waste will result from power plant operation which require treatment prior to disposal or recycling.

Liquid effluents, resulting for example from wet gas scrubbing and flue gas condensation, must be treated. The waste water treatment is conventional, although oxygenated organics such as phenols (derived from tars) and ammonia may create problems. Systems using hot gas filtration are likely to reduce liquid effluents, and could potentially reduce costs and environmental impacts.

Solid residues will consist of inert ash. The ash is likely to be disposed of conventionally through landfilling or used, for example, as a soil nutrient. Care must be taken, however, as dust from fly ash may be toxic because of the absorption of chemicals such as benzo(a)pyrene. Also, heavy metal concentrations in the ash may be too high for the direct recycling of the ash. Research programmes in Sweden have produced promising results with regard to ash recycling from wood gasification and combustion systems. In most cases, ash can be recycled without any further processing other than wetting and crushing it (Nilsson, 1996).

5 Economics of biomass gasification for heat and electricity generation

The economics of biomass gasification for heat and electricity generation is the principal factor influencing its future market penetration. The costs of current and planned demonstration plants are high, and do not reflect the costs of future commercial installations. Detailed data on the costs of the different fuel cycle activities is provided in Annex 1, and Chapters 5 and 7 discuss in detail the costs of gasification-based biomass fuel cycles.

Various authors have estimated that considerable cost reductions could be achieved by biomass gasification systems for power generation, leading to generation costs competitive with those of conventional energy sources. Solantausta et al. (1996) estimate present costs for BIG/CC systems between 30 and 60 MW_e capacity to range between US$2,200 and US$2,700 per kW_e and estimate future capital cost at about US$1,450/$kW_e$ for a 30MW_e installation. Larson and Marrison (1997) estimate capital costs for a 60MW_e LP-BIG/CC plant and HP-BIG/CC plant at US$1,288/$kW_e$ and US$1,425/$kW_e$, respectively. As a comparison, the capital cost of a fluidised combustion/steam turbine (FB/ST) 50 MW_e plant is estimated at US$1,647/$kW_e$. Larson and Marrison (1997) also suggest that the total electricity production cost from a LP system will be lower than from a HP system up to scales of 50 to 80 MW_e. Sydkraft, the owner of the Värnamo demonstration plant, estimates that commercial HP-BIG/CC plant capital costs will be about US$1,500-1,600/$kW_e$ for a 60 MW_e plant (Sydkraft, 1998). Up to capacities of about 30 MW_e, gasification coupled with reciprocating gas engines may possess a lower capital cost compared to combined cycle systems. However, the lower capital cost will have to be traded off against a lower efficiency. Also, the type of application, electricity only or co-generation, will influence choice.

Capital costs alone do not provide sufficient basis for comparison between different energy sources. Variable costs, fuel costs in particular, are of key importance. Biomass fuel costs can vary considerably depending on type and location. For biomass energy to be competitive, an indicative cost of biomass of US$2/GJ or lower is often cited. However, biomass costs could range from negative costs i.e. in the case of waste products, to costs significantly in excess of the suggested cost. Chapters 5 and 7 analyse in detail the costs of biomass fuels derived from short rotation coppice, forestry residues and agricultural residues for particular case studies and discuss the implications of biomass costs on the competitiveness of biomass gasification for heat and electricity generation.

6 Constraints and opportunities affecting the development of biomass integrated gasification systems

Integrated gasification systems for power generation are in the demonstration or early commercialisation stage and their market development will depend on a series of factors. These range from technical developments through energy market structure to government policies with regard, for example, to energy security and the environment.

A number of technical issues need yet to be addressed with regard to integrated gasification systems. The demonstration projects are very valuable in this respect and technical problems do not appear to be a major obstacle to the development of the systems. Clearly, much operating experience, in particular with different types of fuels, is yet required and such experience will require investment in demonstration.

Integrated gasification systems are characterised by high capital costs and, in some cases, high biomass fuel costs which are features common to most biomass energy systems. These are the main barriers to the market penetration of biomass energy systems. However, integrated gasification systems should offer efficiency gains, features such as higher power to heat ratios and environmental benefits which could enhance its viability compared to other systems, in particular with direct combustion systems.

Capital costs for emerging gasification based power generation systems are likely to decrease due to technology development, replication, learning by doing and competition as more suppliers enter the scene. Gasification systems are also likely to be characterised by significant economies of scale. However, cost reductions will only happen through market penetration, leading to the classic chicken-and-egg dilemma. The identification of opportunities for early market penetration is imperative.

Biomass fuel availability generally represents a major constraint on installed capacity which in turn strongly influences the capital cost of the installation per unit of power output. Also, the low energy density of biomass and its transport by road influence strongly the transport costs and therefore the cost of the biomass fuel delivered to the plant. Low cost (or even negative cost in the case of some waste products) biomass resources, short transport distances and efficient logistics for biomass plants e.g. small biomass fuel catchment areas, are very important in the development of biomass energy systems. The issues of security of fuel supply, that is ensuring a fuel supply for the lifetime of the plant, needs to be addressed and is of particular importance in the case of energy crops. Acceptance on the part of farmers is also an issue in the case of energy crops.

Biomass energy is likely to prosper more in a liberalised energy environment in which independent power production and surplus power exports from industry are favoured. Also, regulation or incentives aimed at the reducing emissions may favour integrated gasification systems which are likely to be characterised by low emission levels of regulated pollutants and no CO_2 emissions from the conversion of biomass.

The market potential for gasification technology is substantial based on potential feedstocks (waste products and energy crops). However, growth in its adoption will depend on successful demonstration, energy generation costs, environmental factors, energy market structure, players' attitudes and suitable policy measures in place.

The following chapters will discuss the requirements, constraints and opportunities of biomass integrated gasification systems for heat and electricity based on the analysis of three case studies.

CHAPTER 4

GASIFICATION OF WOODY BIOMASS IN SWEDEN AND THE UK

1 Introduction

The scope of this chapter is to provide a detailed description of two gasification-based biomass fuel cycles in the EU. The case studies selected are the Värnamo Plant in Värnamo, Sweden, and the ARBRE Plant in Eggborough, UK. The chapter provides information on the framework for biomass energy exploitation, including biomass potential, national and local policies, and key players, which is of interest in the assessment of the potential for implementation of the systems considered. Regional environmental and socio-economic information provides the background for the economic and environmental analysis of the biomass fuel cycles. A detailed description of the Värnamo and ARBRE fuel cycles provides a technical discussion, analysing the strengths and weaknesses of the fuel cycles, and provides the basis for the economic and environmental analysis, including the identification of the fuel cycles' priority impacts. Finally, reference systems are defined, which will serve as a basis for comparison to assess the economic and environmental performance of the biomass fuel cycles.

2 The Swedish and UK biomass case studies

The Värnamo Power Plant, located in Southern Sweden, is a demonstration plant and the only example of an operating BIG/CC system. The plant consists of a high pressure biomass integrated gasification gas and steam turbine combined cycle (HP-BIG/CC) system for the generation of electricity for export to the grid and of heat for delivery to a district heating system. Because of the demonstration nature of the plant, various woody biomass fuels are being tested (e.g. forest residues, sawmill residues, short rotation coppice). The present study considers uniquely residues from forest felling operations as fuel. A portion of the biomass used at the plant could be provided by wood waste from sawmills and from the pulp and paper industry or by short rotation coppice.

The ARBRE Power Plant, located in the Northeast of England, is also a demonstration plant. It is currently being built and expected to be completed at the end of 1999. The plant will be fuelled with wood chips derived from short rotation coppice, fertilised with sewage sludge, and from forestry residues to generate electricity via a low pressure biomass integrated gasification gas and steam turbine combined cycle (LP-BIG/CC) system.

Table 8 provides some basic information on the case studies and Figure 7 and Figure 8 show the process flow diagrams of the biomass conversion facilities.

Table 8: The Värnamo and ARBRE case studies

Plant name	Värnamo Power Plant	ARBRE Power Plant
Location	Värnamo, Sweden	Eggborough, UK
Owner	Bioflow Ltd	ARBRE Ltd
Status	Over 1000 hours integrated operation	Construction and SRC establishment phase
Plant type	High pressure BIG/CC	Low pressure BIG/CC
Capacity	6 MW_e, 9 MW_{th}	10 MW_e
Fuel consumption	19 MW_{th}	25 MW_{th}
Annual operation	4400 h	7460 h
Fuel type	Wood chips from forestry residues	Wood chips from SRC and forestry residues

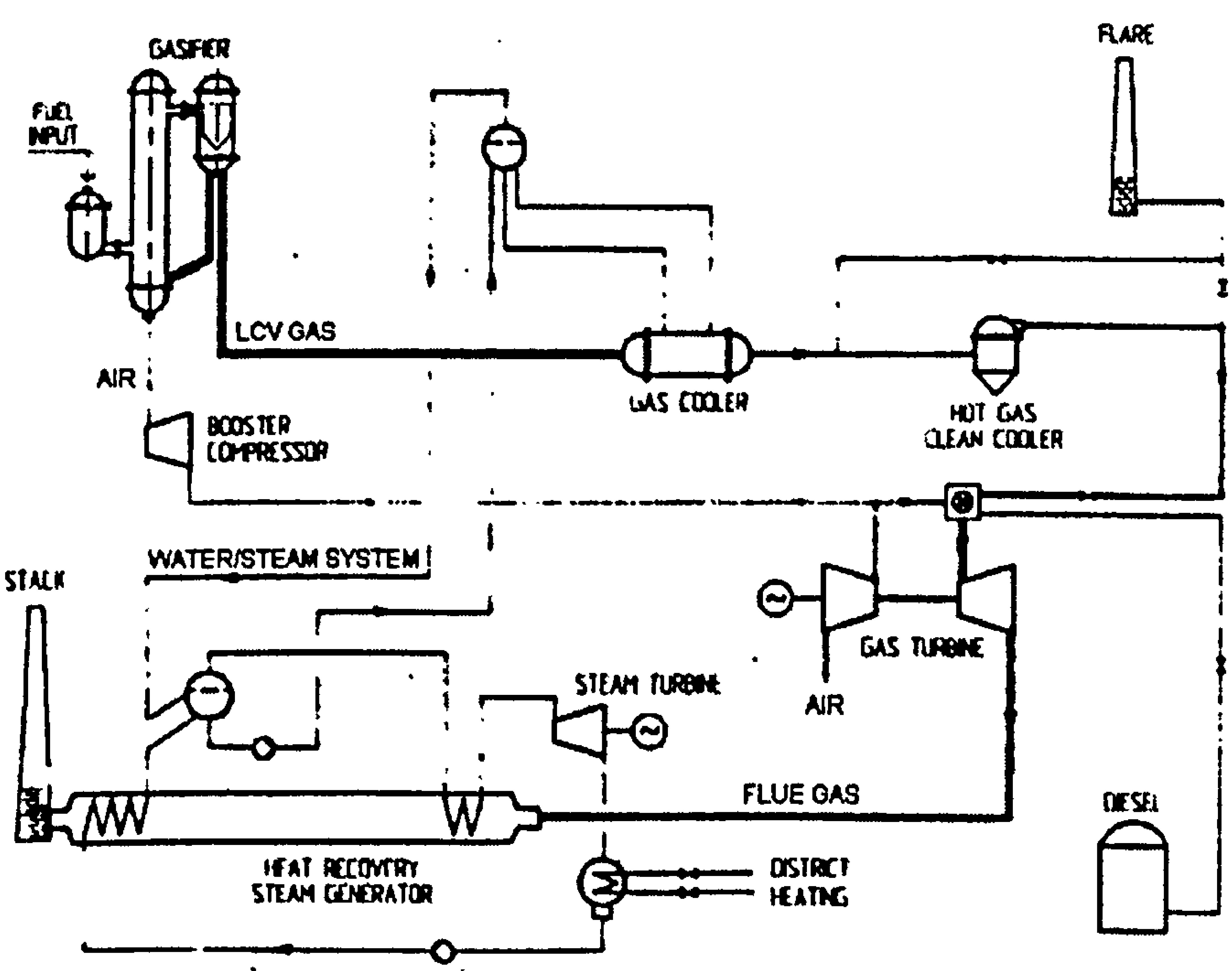

Figure 7: Värnamo plant process flow diagram (Source: Bioflow Ltd)

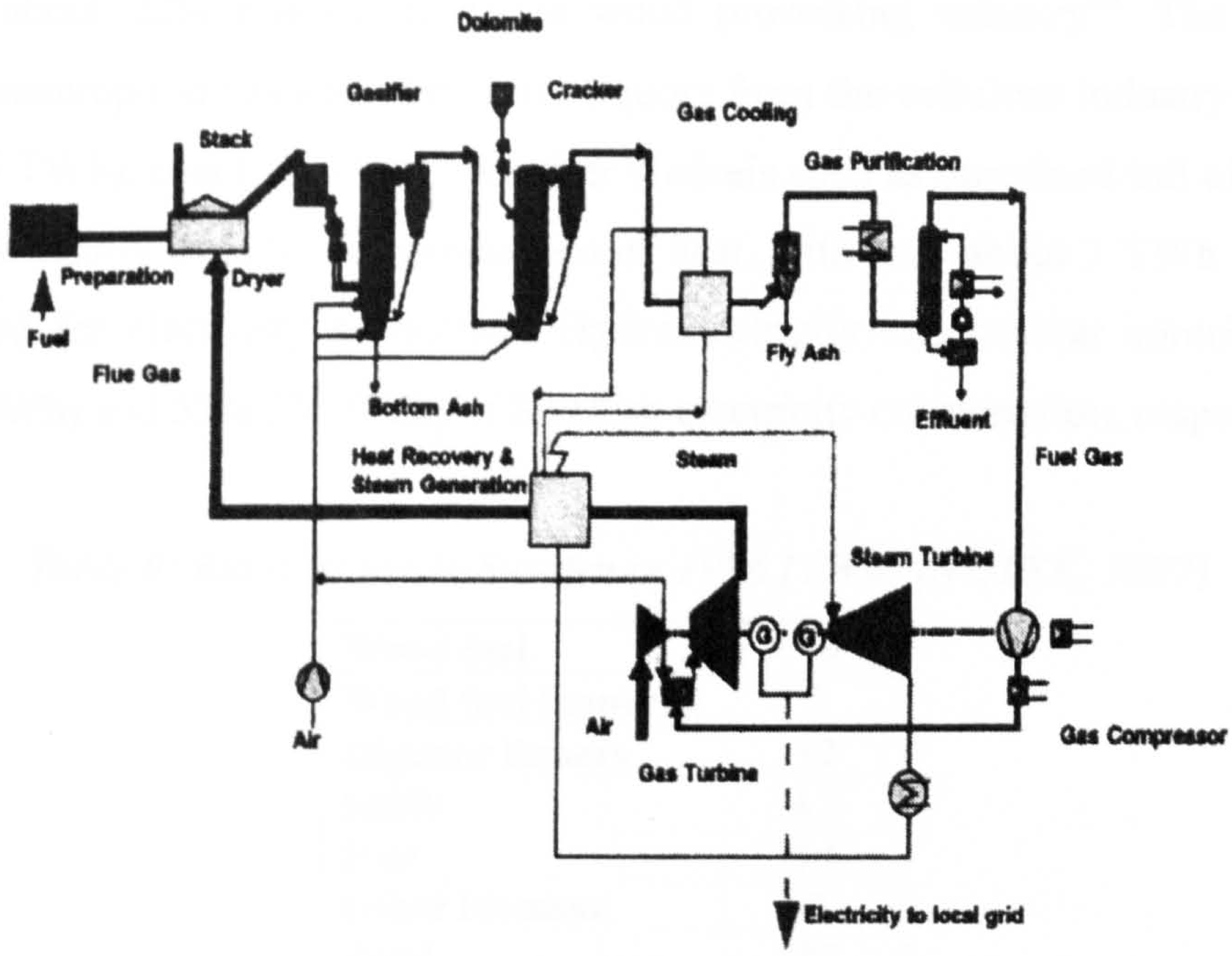

Figure 8: ARBRE plant process flow diagram (Source: ARBRE Energy Ltd)

3 The framework for biomass energy in Sweden and the UK

The availability of a secure biomass resource is an evident condition for the implementation of biomass energy systems and must be carefully considered. Biomass energy projects must be implemented in a framework which cuts across issues of agriculture, forestry, energy, rural development and the environment. In each of these spheres, policies, laws, institutions and attitudes have developed, often creating opposing forces which affect the feasibility of biomass energy projects. This framework is rapidly changing, particularly with regard to agriculture, energy and the environment. The breadth and variability of factors, which affect the market penetration of biomass for energy, make it difficult to draw a conclusive picture of the framework.

3.1 Biomass energy potential in Sweden and the UK

3.1.1 Biomass potential in Sweden

Primary energy demand in Sweden in 1996 was about 485 TWh. Biomass contributed about 87 TWh (Table 9), representing about 18% of the primary energy demand (NUTEK, 1997). Wood fuel consumption, consisting of logs, wood chips, sawmill waste and processed wood fuels like briquettes, pellets and wood powder is estimated at about 45 TWh, of which about 3-5 TWh consist of imported biomass. Wood fuel contributes about 48% of the biomass primary energy, consisting of about 26% forest fuel[9] and about 22% residues from the wood processing industry[10]. The remaining biomass consumption consists of digestor liquors from the cellulose industry (32 TWh), refuse (4.5 TWh), peat (3.5 TWh) and other biofuels such as unrefined tall oil (2 TWh). Biomass is mainly used for the production of heat, with only about 3 TWh of biomass energy used for electricity production. Hydroelectricity and nuclear contribute about 37% (52 TWh) and 52% (74 TWh) of Swedish electricity consumption, respectively.

Table 9: Biomass use in Sweden in 1996 [TWh] (NUTEK, 1997)

Wood fuel	40
Wood fuel (imports)	5
Digestor liquors	32
MSW	4.5
Peat	3.5
Other biomass	2
Total	*87*

About 60% of land area in Sweden is covered with forests, of which only about 5% is considered natural forest. Estimates of wood fuel potential vary widely, ranging between 15 and 125 TWh/yr (excluding current use) (Börjesson et al., 1997). Figures quoted in Jörgensen et al. (1998) estimate forest fuel potential in Sweden at about 165 TWh/yr, and the potential for Southern Sweden at about 46 TWh/yr (50% logging residues; 22% thinnings; 17% whole trees from initial thinnings; 11% felling for fuelwood). About 69% of the land area in the Jönköping county, where the Värnamo plant is situated, is covered by forest, and the potential for the county is estimated at about 6 TWh/yr.

Potential estimates for short rotation forestry and energy grass range between 13 and 59 TWh/yr, and the straw potential is estimated at between 6 and 11 TWh/yr (Börjesson et al., 1997).

The above biomass resources could be used in future BIG/CC systems to generate heat and electricity with an overall efficiency of about 85% and a power to heat ratio of about 1, or electricity only with an efficiency of about 42%.

[9] Forest fuel consists of felling residues (mainly branches and tops), bark and wood from the trunks.
[10] Mainly wood waste from sawmills and from the pulp & paper industry.

3.1.2 Biomass potential in the UK

In 1997, renewable energy contributed about 1% (27 TWh) of the UK primary energy demand (2,640 TWh). Biomass (including MSW) contributed about 0.8% (22 TWh) of the primary energy. A breakdown of the biomass energy contribution is given in Table 10.

Table 10: Breakdown of biomass contribution to renewable energy supply in the UK in 1997 [TWh] (DTI, 1999)

Landfill gas	3.6
Sewage sludge	2.2
Domestic wood	2.4
Industrial wood	5.9
Straw combustion	0.8
MSW combustion	5.0
Other biomass	2.1
Total	*22*

The following potential estimates focus on woody biomass and straw as fuels for BIG/CC systems for electricity generation.

Energy Crops

ETSU (1994b) has estimated that 1.0 to 1.5 Mha of the available land area used for agriculture (i.e. about 18.5 Mha, of which 4 Mha consist of arable land used for cereal cultivation) may become surplus to requirements for food production by 2000 and about 5.5 Mha by 2010. Assuming yields in the range 15 to 21odt/ha, it estimated a biomass potential from SRC of 15 Modt in 2000 and 115 Modt in 2010, which could contribute 31 to 241 TWh/yr of electricity based on a BIG/CC electrical conversion efficiency of 42%. Additional to this, there would also be possibilities of growing energy crops on reclaimed and marginal land.

The above SRC potential estimates are likely to be high. Assuming that between 5 and 20% of the 4 Mha of arable land is dedicated to energy crops and that yields range between 10 and 15 odt/ha/yr, the available biomass resource would be between 2 and 12 Modt/yr. Alternatively, the assumption that 10% (1.85Mha) of all agricultural land were destined to energy crops would imply an available biomass resource between 18 and 28 Modt/yr. The uncertainty over the amount of land which could be dedicated to energy crops leads to a wide range for electricity production from SRC, estimated at 4 to 59 TWh/yr.

The potential biomass resource from energy crops is large, in particular in predominantly arable areas such as that where the ARBRE project is located. However, there are considerable uncertainties on the evolution of agricultural policy and on land availability for non-food crops. Also, farmers' interest in growing energy crops is uncertain.

Forestry residues

The UK is one of the most sparsely wooded countries in Europe, with only about 10% of its land area (2.7 Mha) covered with trees, predominantly in Scotland and Wales.

DTI (1999) provides estimates for the current and future UK forestry residues resource (Table 11).

Table 11: Forestry residues resource estimates for the UK (DTI, 1999)

	Wood fuel resource [TWh]	
	1998	2013
Residues and residuals	1.54	3.30
Wood processing waste	0.74	1.90
Broadleaf woodland	1.02	1.02
Arboricultural residues	2.42	2.42
Total	*5.72*	*8.64*

Assuming a 42% electrical conversion efficiency in the case of BIG/CC systems, the forest residues resource could contribute about 2.4 TWh/yr of electricity based on the current resource estimate and 3.6 TWh/yr based on the future resource estimate.

In Northeast England, forestry activities produce about 40,000 dry tonnes of residues per year. This could theoretically supply about 84 GWh/yr of electricity. Approximately 75% of this resource is available in the Kielder Forest in Northumberland, which is over 150 km north of the study site.

Agricultural wastes (straw)

Approximately 12.5 Mt (c. 15% moisture content) of straw is produced annually in the UK, of which close to 70% is estimated to be used mainly within agriculture. The quantity of straw potentially available as a fuel is estimated at about 4 Mt. Assuming a

42% electrical conversion efficiency in the case of BIG/CC systems, straw could contribute about 7 TWh/yr of electricity. The amount produced is also very much dependent on agricultural policy (e.g. set-aside) and on the other uses of straw. It is estimated that straw could be delivered to the plant at a price of £25/t (ETSU, 1994b).

3.2 The national framework

3.2.1 The Swedish national framework

Biomass has always been an important source of energy in Sweden. Although its importance decreased after the Second World War, its use has again been increasing since the early 1970s for energy security and environmental reasons.

The promotion of biomass energy has been achieved through information and demonstration programmes such as the Energy Technology Fund, established to co-ordinate government investment in the development of technology for renewable energy sources, and the Fabel programme providing support for pilot projects for the generation of electricity from biomass. Swedish energy policy has also included investment support, in particular to combined heat and power and to district heating schemes. However, economic policy instruments in the form of environmental taxes and levies have been the most successful in the promotion of biomass energy.

Sweden introduced a CO_2 tax in 1991 at a level of €0.03/kg CO_2 and a sulphur tax at a level of €3.5/kg of S. In 1992, an environmental levy on nitrogen oxides emissions was introduced at a level of €4.7/kg NO_x. The levy is neutral with respect to the national budget, as the income generated by the levy is redistributed to the operators with low emissions. Biomass fuels are not subject to the CO_2 or sulphur tax, but are subject to the NO_x levy.

Energy producers have reacted quickly to economic policy instruments intended to influence the supply of energy. The economic instruments have been aimed mainly at the heat supply market and have resulted in a significant increase in biomass use to this end. They have not however affected electricity generation and thus biomass use for electricity remains marginal (Hillring, 1998).

Recent news (Eurorex Newsletter, 1999) indicates that half of all planned bioenergy projects in Sweden may be postponed or even abandoned due to the low electricity prices. This may substantially alter the development of the Swedish energy system, as the use of biomass for heating and co-generation was planned to play a major role the country's development. The current price of electricity on the market is about 15 öre/kWh (m€17/kWh) and has been as low as 8 öre/kWh (m€9/kWh) on the spot market, while it is estimated that the price should be around 30 öre/kWh (m€34/kWh) for biomass electricity from the planned systems to be viable. The evolution of the electricity price in the newly liberalised market is a major determinant in the development of biomass energy.

3.2.2 The UK national framework

The UK government policy has been "to stimulate the development of renewable energy sources, wherever they have prospects of being economically attractive and environmentally acceptable, in order to contribute to: diverse, secure and sustainable energy supplies; the reduction in the emission of pollutants; and the encouragement of internationally competitive industries." (DTI, 1994). However, the contribution of renewable energy remains low and represents only about 2% of present electricity supply. The current UK Government has a Manifesto commitment to "a new and strong drive to develop renewable sources of energy". Its aim is to achieve 10% of UK electricity requirements from renewables by 2010, with 5% of electricity provided by renewables by 2003. In its recent Renewable Energy Review (DTI, 1999) it undertakes a review of the status and prospects of renewables, including an examination of what would be necessary and practicable to achieve the aim and what contribution renewables could make to reducing greenhouse gas emissions. Biomass is seen as an important contribution to meeting the 10% target.

The Non-Fossil Fuel Obligation (NFFO) is the main policy tool used to stimulate the development of this generating capacity. Under present arrangements almost all renewable energy projects in the UK are dependent on guaranteed premium rates for the electricity they sell. These are financed by a surcharge on consumers' electricity bills (the Fossil Fuel Levy) used to reimburse the Regional Electricity Companies (RECs), which are required to buy the electricity under the Non Fossil Fuel Obligation (NFFO). Generators are guaranteed a premium price for the duration of their contract (15 years in the case of the latest contracts under NFFO4). Contracts are awarded on the basis of a competitive bidding process. The aim is that in successive rounds of the NFFO the premium price is gradually reduced, so that it converges with the market price of electricity. The ARBRE plant has received funding under the NFFO scheme. Some support also exists for the development of energy crops, for example in the form of the Forestry Commission SRC establishment grant.

3.3 The local framework

3.3.1 The Swedish local framework

In Sweden, the borough council is responsible for detailed planning and implementation of the general policy principles decided at national and county levels. The Värnamo council has a renewable energy plan, which involves extending the district heating grid and is likely to require the construction of two new biomass burning heat facilities. This is part of a strategy to reduce local consumption of electricity by 1% per annum from 1995 to 2015, under their Local Agenda 21 programme. Outside central Värnamo it would be uneconomic to supply district heating, so the council is also encouraging more remote households to use modern wood pellet burning stoves. Biomass for energy is seen as attractive by the local government for a number of reasons, but perhaps the most important reason is that it creates more local employment than other forms of energy.

3.3.2 The UK local framework

In the UK, local planners must take into consideration national policy goals and development plans agreed at the county and district levels in making their decisions on a given development application. Biomass energy schemes are seen favourably for their contribution to rural employment, and local planners are encouraged to give proper consideration to renewable energy developments by the national government. However, practical advice on the matter is scarce. Planning Policy Guidance Note 7, on The Countryside and Rural Economy, since 1992 has acknowledged that retaining land in agricultural production is no longer a strong priority, and diversification is encouraged. Planning Policy Guidance Note 22 indicates that local planning authorities should include renewable energy in their development plans, on the basis of the 'contribution their area might make'.

3.4 Key players

3.4.1 Power plant developers

In Sweden, government energy and environmental policy has aimed at the promotion of biomass energy through a series of economic instruments. Energy companies, including the two largest, Vattenfall and Sydkraft, have then become strongly involved in biomass energy. Vattenfall and Sydkraft own a large number of biomass fuelled plants, in particular for district heating. Sweden's commitment to nuclear power plant phase-out and the gradual liberalisation of the energy market should lead to an increase in the number of biomass fuelled combined heat and power (or power only) plants. The involvement of small independent generators is also likely to increase.

The large electricity companies in the UK have shown little interest in renewables, biomass in particular. However, there is some evidence that they are increasingly interested in direct ownership of renewable generating capacity. In the third round of NFFO, bids were received from three large electricity companies to develop wind farms, and, following a US trend (Wiser, 1997), large power company ownership of wind farms is becoming more common. In the UK, experience with gas fired generation may be helping overcome the inertia in the utilities' preference for large centralised generation. Also, electricity market liberalisation is likely to favour shorter lead times, greater flexibility and smaller unit size (Patterson and Grubb, 1996 and Patterson, 1999). To counteract this optimism, increased liberalisation may mean less state support for renewables, and the ability of biomass to compete with conventional sources of electricity (e.g. natural gas) on price terms is constrained by the higher capital costs incurred.

Some small private companies are active in generating electricity from renewables, but two major obstacles limit the involvement of small independent generators in the biomass field. Firstly, there is a lack of awareness in the business community of the very concept of biomass energy. This reflects the limited experience of biomass for power generation in the UK, poor public awareness in general, and possibly a poor image of biomass as a fuel of the past (wind and solar benefit from a hi-tech, 'forward looking' image). The second major obstacle is the access to appropriate resources and financing. Simply providing the resources for making a NFFO application may be off-putting to a small company unsure that its bid will be successful. This problem is exacerbated by the fact that a NFFO contract is no guarantee that a project will go ahead, as it could fail to secure planning permission (another lengthy and costly process). Finally, the financial backing to biomass energy schemes is often lacking because of perceived risks associated with the fuel cycle. Several projects which pass the NFFO selection procedure have failed to go ahead because they find they cannot, in fact, supply electricity at the contracted price.

The major players in the renewables business in the UK are new companies which are owned by or closely affiliated to ex-nationalised industries. Water companies and RECs (Regional Electricity Companies, primarily concerned with transmission from the national grid to consumers) have been particularly successful in securing NFFO contracts. In NFFO3 three biomass gasification projects were awarded contracts: two were awarded to a REC (Southwest Electricity Board - SWEB) and the other was awarded to ARBRE Ltd, a company initiated by Yorkshire Environmental which is a fully-owned subsidiary of Yorkshire Water. However, difficulties in the biomass fuel cycle (e.g. securing fuel supply) have caused SWEB to back down from their intentions to build the two gasifiers and the projects have been acquired from them by a small renewable energy company.

The involvement of these companies results from their experience with large engineering projects and experience in the electricity supply industry (e.g. Yorkshire Environmental had previous experience in wind power), possible financial backing from a parent company, and additional interests (e.g. the advantages RECs can derive from embedded generation and Yorkshire Environmental's interest in SRC plantations for sewage sludge disposal). Also, the category of REC as a key actor in this framework reflects the present arrangement under which sale of electricity to a REC under a NFFO contract is the only way in which a biomass power project can secure a market. In its actions aimed at the disintegration of the supply and distribution activities in the electricity sector, the government is looking closely at arrangements to ensure that embedded generators (i.e. those directly connected to local distribution systems - as is often the case with renewable energy suppliers) receive a fair price for their electricity.

Due to the pricing structure, buying from an embedded generator can actually be cheaper for a REC than buying from the pool. RECs then avoid paying the administrative charge for the pool ('uplift') and the charge made for transmission losses in the grid (about 2% of the total). Additionally, the National Grid Company normally charges an 'Infrastructure Tariff' to cover the cost of system reinforcement. This tariff is reduced if a REC has embedded generation operating at times of peak load (since it effectively defers the need to reinforce the system). Biomass power stations are not intermittent and can be scheduled to operate at peak load. Losses within the REC's lower voltage distribution network will also be reduced, and they may be able to defer investment in its reinforcement if embedded generation is located near demand. The resulting financial benefit is substantial to the REC, and there is pressure on the industry regulator (OFFER) to force RECs to share some of this benefit with the generators. Preliminary analysis has found that the value of embedded generation to a REC relative to the pool purchasing price could be 0.8 - 1.2 p/kWh (about m€10 - 14/kWh) (Taylor, 1996).

3.4.2 Fuel suppliers

The two major sources of wood fuel considered are from forestry residues and from short rotation coppice. Most wood fuel is obtained from conventional forestry.

In Sweden, the wood fuel market is relatively well established and has grown significantly in the last two decades (Hillring, 1997). Wood fuel price has remained constant during this time at about US$4/GJ (€3/GJ), representing a price drop of almost 50% in real terms. The price trend is in part a result of the large quantities of wood fuel still available for supply in Sweden. Prices are related to the actual biomass fuel production costs but are also influenced by price trends of fossil fuels and other alternative fuels and by competition between different biomass fuels.

In the UK, there is a small existing market for wood chips for mulch (in gardens) and for domestic fuel. Additional resource is available in the UK, provided that the wood fuel price is sufficient to compensate for the cost of wood fuel production.

Forestry operators are generally keen to collect residues, as it reduces a waste problem, improves access to forests, enhances recreation value, allows easier replanting, and possibly reduces pest problems and soil acidification. However, residues collection implies costs and private entrepreneurs will only undertake the task if profits are to be made.

The key players in wood fuel supply are forest owners, forest fuel entrepreneurs (i.e. those who collect and chip the forest residues) and forest fuel contractors (i.e. fuel brokers). Different levels of business integration are possible in the fuel supply chain (e.g. the forest owner and forest fuel entrepreneur could be one entity).

Wood fuel can also be supplied from agriculture. Currently, over 16,000 ha of short rotation coppice are grown in Sweden. In the short-term there appears to be little interest in dedicated energy crops such as SRC, not because of lack of land availability, since the agricultural area is contracting, but because the local forest residues resource is very large and SRC is not seen as an economically viable option. The situation may change in the future if the biomass energy sector expands.

Commercial SRC schemes in the UK cover only a few hundred hectares. The National Farmers' Union (NFU) and most of its members are keen to diversify into new crops, and are particularly keen to make productive use of set-aside land. The rapid take-up of oil seed rape is evidence of this enthusiasm. However, the policy climate is unfavourable for farmers to make the long-term commitment necessary for the success of perennial crops such as SRC. The price for wood that biomass plant owners would be willing to pay would presently make it unprofitable for farmers to contract to supply from land that is not receiving set-aside payments or other grants (e.g. Forestry Commission SRC establishment grant).

The ARBRE project is likely to expand the commercial SRC area to over 2,000 ha over the next few years. The fuel supply is contracted to Border Biofuels, a company with expertise in growing SRC. To identify farmers in the local area that might be interested in growing SRC, the NFU provided lists of local farmers with arable land in set-aside. These were then contacted, and invited to open days where the crop management could be seen first hand. The response was disappointing, despite the favourable terms offered to farmers. The farmer is responsible for ground preparation prior to planting, but all subsequent work is the responsibility of Border Biofuels, thus reducing obstacles related to the poor experience of farmers with SRC. Interim payments are offered (in addition to set-aside payments and establishment grants) to spread the revenue over the years between harvests. The lack of interest from farmers remains a significant obstacle, although information campaigns, active engagement with the farming and local community and the first experiences of some farmers are starting to attract increasing interest.

3.4.3 Public support and resistance

The environmental benefits of biomass compared to alternative conventional energy options are increasingly being recognised and support from environmental groups is growing. Environmental benefits and advantages in terms of energy security and employment in rural areas are also increasing government and local authorities' attention to biomass energy. However, information dissemination on the possibilities of biomass energy to industry, local government and to the public remains generally inadequate.

Gaining planning permission for a facility remains a major hurdle. Negotiating the planning process is a difficult, costly and time-consuming process. In Sweden, the public's attitude is generally favourable to renewable energy installations, biomass in particular. There was no significant opposition to the building of the Värnamo Power Plant. The ARBRE project in the UK was also successful in its planning application. Nonetheless, in the UK there appears to be no presumption in favour of renewable energy developments and opposition to developments on the part of local planners, and the local opinion they are answerable to, is not uncommon. The NIMBY ('Not In My Back Yard') attitude appears more acute for rural power generation and to be more pronounced in the UK compared to Sweden. The NFFO process tends to create tensions within the planning process. Acceptance under NFFO in no way prejudices the planning authority in favour of the project. Early involvement of the planning authorities and of the public is important for the successful implementation of a project.

Biomass trade organisations such as SVEBIO (http://www.svebio.se/) in Sweden and British Biogen (http://www.britishbiogen.co.uk/) in the UK are active in the promotion of biomass energy.

4 General regional information

Regional information is fundamental in the assessment of the potential impacts of biomass fuel cycles. Information on air, soil and water media is a basis for the determination of the potential environmental impacts. Information on socio-economic aspects, such as unemployment, is necessary in determining economic and social implications of the fuel cycles. The regional conditions also influence the attitude of the public toward the development of biomass fuel cycles. The remainder of this section provides information on the regions in which the Värnamo and ARBRE power plants are sited.

4.1 Swedish regional information

4.1.1 Air quality

Two million people, about one third of the adult population and 40% of children, in Sweden are affected by increased sensitivity to air pollution. Air quality in Jönköping county, where Värnamo is situated, is within the government emission target levels, with per capita emissions in the county generally below the national average. The installation of district heating systems, in particular biomass fuelled ones, is estimated to have significantly reduced emissions of SO_2, NO_x and particulates compared to the use of residential boilers.

4.1.2 Water and soil quality

Acidification of soil and water is a major issue in Sweden. pH levels in forest soils have been increasing over the last 50 years and acidification represents a considerable risk of lasting damage to vegetation, mainly through the mobilisation of metals present in the soil. Minor water courses, rivers and lakes are also affected by acidification. Acidified water and increased levels of metals such as aluminium, iron, manganese and mercury affect the biodiversity of the water bodies. In the early 1990s annual sulphur deposition in Sweden was estimated at about 300,000 tonnes of which close to 90% consisted of deposition from abroad (Norway, UK, Denmark, Germany, Czechoslovakia, Poland, former Soviet Union and Finland). Nitrogen deposition was estimated at about 164,000 tonnes, of which close to 80% consisted of deposition from abroad.

Eutrophication is also considered a problem in Sweden. A sixth of all lakes larger than 1 ha (about 15,000 lakes) are considered eutrophic (phosphorous level > 25 μg/l) and about 80 lakes and bays are considered hypertrophic (phosphorous level > 100 μg/l).

Southern Sweden is most affected by acidification. It is considered the most serious environmental problem in Jönköping county and given high priority in the regional environmental plans. Critical loads of sulphur and nitrogen deposition are exceeded in the entire county, and it is estimated that about 50% of the surface waters in the county could be affected by species loss. An extensive liming programme has been undertaken to counteract acidification in the regions surface waters. The total cost of the liming activities in the county was estimated at SEK15.7 million (c. €1.7 million) in 1997. Between 20 and 40% of forest soils in the county could be suffering from acidification.

A major concern expressed by the local government is that liquid emissions from the flue gas cleaning and condensation at the drying plant could contaminate local sewage, making it unusable for agriculture. This is not a source of local opposition, since most people are not aware of the potential problem. However, it has great strategic importance for the council, since there is a national programme aimed at expanding the use of domestic wastewater to displace the use of chemical fertilisers in agriculture. Sufficient precautions and communication between the plant operators, the local government and water authorities should avoid any problems associated with the issue.

4.1.3 Employment

The local rate of unemployment is 4%, which is low by international standards. Nonetheless, this represents 800 unemployed persons in the Värnamo council. It is estimated that plans for greater use of biomass energy and extending the district heating system will create 100 new full-time jobs (Egerhag, 1998).

4.2 UK regional information

4.2.1 Air quality

The ARBRE power station is to be located adjacent to National Power Plc's Eggborough power station, which is a 2000 MW coal fired facility, between Drax (4000MW$_e$, coal fired) 9 km to the east, and Ferrybridge (2000 MW$_e$, also coal fired) 10 km to the west. Local air and water pollution are severe. The background concentration of SO_2 is approximately 47 $\mu g/m^3$ (annual mean), and the EU guideline concentration 'for the long term protection of human health and the environment' is 40 - 60 $\mu g/m^3$. SO_2 emissions from the ARBRE plant are likely to very small and estimated to contribute 0.3 $\mu g/m^3$ (ARBRE Ltd, 1996a). NO_x pollution is also high in the region. During start-up of the ARBRE power station (when fuel oil is used) short term NO_x concentrations in its immediate vicinity could exceed EU and World Health Organisation limit values, due to the high background concentrations. Acidification is a problem in the study area, with critical loads exceeded by 50 - 100% in the Vale of York (Metcalfe and Whyatt, 1995). The coal fired power stations have been identified as the cause. Acidification is of particular relevance because of the possibility of heavy metals being added to soils in sewage sludge and wood ash, which become more mobile under acidic soil conditions.

4.2.2 Water and soil quality

Immediately below the ARBRE site the groundwater is contaminated by sulphates and nitrates, and has high concentrations of iron and manganese. The site overlies a highly permeable aquifer and the soils have a low attenuation potential. This means that any pollutants will rapidly reach the aquifer and disperse. The site is within the Pollington Nitrate Vulnerable Zone (NVZ), designated as such under the new EU Nitrate Directive (91/676/EEC). It is not likely that the power plant site itself will cause pollution to groundwater, but nitrates in sewage sludge applied to agricultural land may pose a threat to NVZs.

Surface water quality is also poor in the vicinity of the plant. The River Aire is classified by the National Rivers Authority as Class 3 Poor for chemical content and Class B4 (the lowest possible) for biological quality (ARBRE, 1996a). The Ings and Tetherings Drain, which will receive aqueous discharges from the site, is similarly polluted. Extensive precautions are to be taken at the site to avoid harmful emissions to water courses.

The predominant soil types in the region surrounding (i.e. within a 50 km radius) the ARBRE power plant are the following (Jarvisra et al, 1984): Foggathorpe 2 Association, Romney Association and Newport 1 Association. The latter soil association covers only approximately 5% of the region, but is of importance because it is the soil type in the immediate vicinity of the power plant site. It is a freely drained medium sandy soil, formed on glaciofluvial sands and gravels. This soil association is situated over a major aquifer, leading to the designation of the area as a NVZ under EC legislation. Farmers receive subsidies to use low nitrogen farming practices, and SRC is specifically disallowed as a crop if farmers wish to receive this payment. The area is also prone to wind and water erosion. Otherwise, soil erosion is generally not considered a problem, except some wind erosion of fine sandy soils just Southeast of York. Land is fairly flat in the region and most of the soils present are generally low in permeability and prone to waterlogging in winter and some droughtiness in summer.

4.2.3 Land availability

The ARBRE project developers estimate that 2,000 ha of SRC will be required, which implies a yield of 14 odt/ha/yr exceeding their own optimistic estimate of average yields of 12 odt/ha/a. A more realistic estimate of the land area required would be 2,800 ha, based on an average 10 odt/ha/yr yield.

Land availability should not be a problem as this is a predominantly arable area, where one can expect large areas of land to be withdrawn from conventional crops production under the set-aside arrangements or to switch to economically viable alternative crops (e.g. energy crops). The developers expect that 'up to 20,000 ha of land' will become available in the region. An area of 2,800 ha represents less than 0.5% of the surface area within 50 km of the facility. However, the set-aside regulations have been uncertain in recent years, and farmers have proven reluctant to commit land to SRC. It is now thought that predominantly forest residues will be used in the first few years of operation, since SRC is being established at a slow pace.

4.2.4 Employment

The project is estimated to create some 40 full time jobs. 20 of these will be employed in the growing, harvesting and transportation of the fuel, and 20 will be employed to operate the facility.

5 The Värnamo Power Plant

The Värnamo Power Plant is owned and operated by Bioflow Ltd. The company is a joint venture established in 1992 between the Pyropower sector of A. Ahlström Corporation (now part of Foster Wheeler International Energy Corporation) and Sydkraft (the second largest Swedish energy utility). Its mission is to promote the development and marketing of a pressurised BIG/CC system. The commissioning of the plant was completed in April 1996, and it started operation in September 1996. The demonstration and development phase is expected to last until the year 2000 to test system reliability and potential.

The plant has a gross electric power capacity of 6 MW_e (4.2 MW_e gas turbine, 1.8 MW_e steam turbine), leading to a net power output of 5.8 MW_e, and a thermal power output of 9MW_{th} for district heating. While such a system has the potential for high generating efficiencies, the demonstration nature of the plant places emphasis on the successful operation of the integrated gasifier combined cycle system rather than on the system efficiency. Consequently, the plant has a low electrical efficiency of about 32%. The plant investment cost is estimated at €28 million.

At the beginning of 1999, about 5,000 hours of gasification have been achieved and about 1,300 hours of integrated gasification-gas turbine operation, with a longest continuous integrated operation of about 250 hours. Mostly, operation has been of the combined cycle type with generation of electricity and heat for district heating. The gasifier functions reliably and no problems have so far been encountered with the firing of the producer gas in the gas turbine. Most operational problems have occurred within the feeding system and the bottom and fly ash purging systems. The performance of the hot gas filter has been satisfactory, and has not caused significant pressure drops within the system. However, mechanical failure of a ceramic candle has occurred leading to the shutdown of the plant.

Rape seed oil is used in vehicles for on-site transportation. This is an interesting step towards reducing the non-renewable inputs to the biomass fuel cycle, as well as its environmental impacts.

5.1 Biomass fuel production and transport

The plant requires about 22,000 tonnes (30% moisture content) of forest fuel, equivalent to about 100,000 m^3 (in the form of wood chips). This represents about 1,100 truck loads of wood chips per year.

5.1.1 Fuel characteristics

A typical heating value for woody biomass fuels is about 18GJ/odt (odt: oven dry tonne) and the moisture content of forestry residues at harvest is between 30 and 60%

on a weight basis. The ash content of forest fuels is low and situated between 0.5 and 2%. The ash resulting from the conversion of wood fuels is generally free of toxic metals and other trace contaminants and possesses fertiliser value as it may be used to replenish nutrients (e.g. potassium and phosphorous). Wood fuel also possess a very low sulphur content of about 0.01 to 0.1% by weight. As a comparison, the sulphur content of coal ranges between 0.5 and 5%. The bulk density of wood chips is about 200kg/m^3.

5.1.2 Biomass fuel production and transport activities

Managed forests in Sweden consist principally of two types of trees, spruce and pine. Trees are generally felled after about 80 years, with two minor cuttings occurring after 30 and 50 years of growth approximately. The average forest residues availability in the region considered is estimated at 30 odt/ha. Leaves, branches and tops from logging operations are left in the field and approximately three quarters of those residues are subsequently collected by forwarding vehicles and stacked into piles, which are covered with paper. At a later time, a mobile chipper and container are used to chip the wood. About 300m^3 of wood chips are produced during one 8 hour shift. The total investment cost of the forwarder and chipper is about €300,000. The wood chips are tipped into the container of a shuttle vehicle and transported to the edge of the field, accessible to trucks, where they are tipped in containers of a capacity of about 35m^3. The investment cost of the shuttle vehicle is about €200,000. The containers are then loaded onto trucks for final transportation of the wood chips to the power plant. A truck will transport three covered containers corresponding to a total volume of about 90 m^3 and a total weight of about 35 tonnes. The average transport distance is about 75 km and a truck can complete about 4 to 5 return trips during a 12 hour shift.

The extraction of forestry residues affects the organic component of the soil, its nutrient and pH levels and may also affect natural habitats. The operations associated with the production and transport of the forest fuel are a source of emissions and have other consequences which lead to environmental and socio-economic impacts.

Table 12 summarises the main activities of the biomass production and transport stage of the Värnamo fuel cycle and lists their consequences and relative impact categories.

Table 12: Activities and impacts of the biomass production and transport stage (Värnamo Plant)

Activity	Consequence	Impact category[1]
Collection and chipping of forest residues	Soil compacting and erosion	Forestry yield Eutrophication impacts Rural amenity (e.g. recreational value of water courses)
	Air emissions from machinery operation	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Fossil fuel consumption	*Resource use*
	Noise from machinery operation	Rural amenity
	Labour requirement for machinery operation	*Employment*
	Forestry residues removal	Forestry yield *Acidification impacts (reduced)* *Biodiversity* *Rural amenity* (e.g. recreational gains from enhanced access)
Biomass transport	Air emissions from vehicles	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Fossil fuel consumption	*Resource use*
	Road accidents from vehicle use Labour requirement for vehicle operation	*Human health* *Employment*
	Road use	*Rural amenity* (e.g. road congestion and damage, noise)

[1] Potential priority impacts are shown in italic.

5.2 Biomass conversion

The Värnamo plant has a large uncovered storage area since the fuel pre-treatment plant associated to it serves a number of other biomass conversion facilities. The wood chips are transported to the plant and are tipped into the unsheltered storage area and stored in piles about 8m high, 30m wide and 90m long. For fire safety reasons large corridors must separate each pile.

Prior to its pre-treatment, the fuel is stored under a shelter. It is then transferred by conveyor belt to the pre-treatment facility where it is crushed, screened and dried to a moisture content of about 15%. Drying takes place in a facility separate from the BIG/CC facility and uses a biomass fuelled rotary kiln dryer. Future plants will have integrated drying systems where the biomass will be dried using the hot flue gas from the power generating unit. Such a process will contribute to a better energy balance of the system and to reduced drying costs.

Odours and dust resulting from the drying process may result in nuisance and health impacts and need careful consideration. Water vapour may have to be condensed and treated, in particular for larger installations. Heat recovered by condensation could enhance the total plant efficiency. In the case of the Värnamo plant, where drying occurs in a separate large drying facility at high heat, drying activities result in the formation of considerable quantities of water vapour containing significant quantities of organic compounds. A wet gas scrubber followed by a flue gas condensation system is used to clean the flue gas from the dryer, mainly of dust and organic compounds such as terpenes, and recover the heat from the water vapour present in the flue gas. The condensed water requires a biological treatment before it can be discharged to the sewage system. Condensed organic compounds from the fuel drying activity possess a fuel value and energy can be recovered from their combustion. Particular care is also required in the design of drying installations to avoid fire and explosion risks.

After drying, the wood chips are stored in silos prior to their input to the gasifier. The material flow characteristics of the stored biomass need to be considered in the design of the intermediary storage system in order to avoid flow problems.

The fuel is fed to the gasifier through a lock hopper system. The lock hopper uses nitrogen as the inert gas, which contributes significantly to the operating costs. In the future a piston feeder should be added to the lock hopper and flue gas from the generating system could replace the inert gas. These modifications will considerably reduce feeding costs. The feeding of biomass into gasifiers has proved to be problematic, with the physical properties of the biomass fuel, such as its size and density, affecting the performance of feeding systems.

The gasifier is of the pressurised air-blown circulating fluidised bed type and operates at a pressure of about 22 atm and a temperature between 900°C and 1000°C (temperatures well below the wood ash melting point which is about 1300°C). The start-up of the gasifier will require an input of diesel fuel, but the resulting emissions are likely to be low under normal operating conditions. The air for gasification is provided by the gas turbine compressor and is further pressurised in a booster compressor. The bed material used in the gasifier has been mainly magnesium oxide, however, the plant will continue testing different bed materials (e.g. sand, alumina, limestone, dolomite and fly ash). The average size of the wood chips fed to the gasifier varies between 2 and 5 cm and the gasifier has been shown to be able to operate with wood chips up to 15 cm long. The gasifier efficiency is between 97 and 99%. The fuel gas composition and heating value on a dry gas basis is shown in Table 13.

Table 13: Typical composition and calorific value of the product gas for the Värnamo Power Plant (dry basis) (Ståhl, 1997)

H_2	9.5-12%
CO	16-19%
CO_2	14-17%
CH_4	5.8-7.5%
N_2	48-52%
CV	c. 5(MJ/Nm^3)

The average water content of the gas is 10 - 12%. A reduction in nitrogen content, by a few percent points, may be desirable to slightly enhance the producer gas calorific value. Limits on levels of contaminants such as tars, alkali metals, particulates and sulphur are very low in order to meet gas turbine specifications. The presence of ammonia in the fuel gas is also of concern as it is converted to NO_x following combustion in the gas turbine.

The fuel gas exits the gasifier at a temperature of about 900°C and passes through a cyclone to remove ash, wood char and bed material which are returned to the bottom of the gasifier. The gas is then cooled in a gas cooler to about 350°C (temperature imposed by the gas turbine operation requirements) and the heat recovered is used to generate steam for the steam turbine.

The fuel gas is then cleaned in a hot gas filter. Testing and demonstration currently underway indicate that environmental and gas turbine fuel requirements can be met with hot gas filtration systems, in particular with regard to the removal of alkali metals. These results are very much fuel dependent. Hot gas cleaning does not remove ammonia from the gas stream, which is instead washed out in a wet gas scrubbing system, and high fuel bound NO_x emissions could result if other means for reducing ammonia levels are not adopted (e.g. catalytic bed material). Hot gas filtration produces a solid waste (dust cake) which can generally be disposed of conventionally with the ash from the gasifier. The dust cake is likely to contain alkali metals which should not present any hazard.

The clean product gas is then burned in the gas turbine combustion chamber (GEC Alsthom Typhoon type turbine). The exhaust gas from the gas turbine is cooled using a conventional heat recovery steam generator (HRSG) producing additional steam for the steam turbine. The gaseous emissions from combustion of product gas are expected to meet the following environmental planning requirements for planning purposes. The actual emissions from the system are analysed in greater detail in Section 4.1 in Chapter 5.

Table 14: Flue gas emissions limits (Ståhl, 1997)

NO_x	<50mg/MJ
SO_x	<25mg/MJ
Dust	<35mg/Nm^3

The exhaust steam from the steam turbine is used to provide heat for the district heating system. The electrical efficiency of the plant is about 32% and the total efficiency of the plant is about 82%. The electrical efficiency of the Värnamo plant is low, but it is estimated that electrical efficiencies of future plants will range between 43% and 50% for an electricity only plant and between about 38% and 45% for a co-generation plant. The total efficiency of the co-generation plant will be about 85%, with a high power to heat ratio ranging between 0.8 and 1.2 (Ståhl, 1997).

Table 15 summarises the main activities of the biomass conversion stage of the Värnamo fuel cycle and lists their consequences and relative impact categories.

Table 15: Activities and impact categories associated with biomass conversion (Värnamo Plant)

Activity	Consequence	Impact category
Plant construction and decommissioning	Air emissions from construction equipment	Human health Acidification impacts Climate change impacts Ecotoxicity (e.g. effect of ozone formation on plants)
	Fossil fuel consumption	*Resource use*
	Occupational hazard	Human health
Biomass storage	Fire hazard	Human health
	Thermophilic fungi formation	Human health
Biomass drying and processing	Emission of organic compounds in water vapour	Human health Eutrophication impacts Rural amenity (odours)
	Dust emissions	*Human health* Rural amenity (visual)
	Noise from machinery operation	Rural amenity
Electricity and heat generation	Flue gas emissions	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Waste water emissions	Human health Ecotoxicity
	Labour requirement for plant operation and maintenance (including pre-treatment of biomass)	*Employment*
	Use of biomass fuel	*Resource use* *Contribution to national balance of payments* Security of supply

5.3 Waste disposal and recycling

The gasification and gas cleaning processes generate solid waste products, in the form of bottom and fly ash and filter cake. The solid residue will consist mainly of pure wood ash mixed with bed material and is not likely to contain significant amounts of hazardous substances. Heavy metals and polyaromatic hydrocarbons (PAHs) will usually be present in trace quantities below the concentration limits imposed by environmental regulations. PAH levels can be reduced by burning the ash, and techniques are also available for the removal of heavy metals. Prior to their final disposal to landfill the ashes are wet and stored on the ground outside the plant. An extensive research programme on ash recycling is ongoing to assess the potential of returning the ash to the soil. The results so far lead to believe that ash recycling as soil nutrient is desirable and does not present adverse environmental effects (Nilsson, 1996). The extent of recycling will also depend on the chemical properties of the soil.

Table 16 summarises the main activities of the waste disposal and recycling stage of the Värnamo fuel cycle and lists their consequences and relative impact categories.

Table 16: Activities and impact categories associated with waste disposal and recycling (Värnamo Plant)

Activity	Consequence	Impact category
Transport of waste	Air emissions from transport of ashes	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Road accidents from vehicle use	*Human health*
	Labour requirement for vehicle operation	*Employment*
	Road use	*Rural amenity* (e.g. road congestion and damage, noise)
Disposal to landfill	Leaching of noxious substances	Human health Ecotoxicity
	Nutrient leaching	Eutrophication
Recycling of ash	Nutrient addition to soil	Soil quality
	Nutrient leaching	Eutrophication
	Leaching of noxious substances	Human health Ecotoxicity

6 The ARBRE Power Plant

The plant is owned by the joint venture company ARBRE Energy Limited formed by Yorkshire Environmental, TPS Termiska Processer, Swalec Power and AEP Associated Energy Projects. The plant, which is in the construction phase and expected to be completed at the end of 1999, will generate electricity and will be fuelled by wood chips, 80% of which should be provided by willow and poplar short rotation coppice (SRC) plantations and the remaining 20% by forestry residues. The ARBRE plant is also being developed principally for demonstration purposes and its electrical efficiency is expected to be similar to that of the Värnamo plant.

6.1 Biomass fuel production and transport activities

The UK presents a very different biomass resources picture compared to Sweden. In the UK forest cover is only about 2 million ha compared to Sweden's 23 million ha. The development of schemes like the ARBRE plant is then likely to rely on biomass contributions from energy crops or possibly wastes from sources such as agriculture and MSW.

The ARBRE plant will require about 50,000 tonnes of wood chips (30% moisture content). An 80% contribution from SRC represents about 40,000 tonnes, requiring some 2,800 hectares of plantation if an average yield of 10 odt/ha/yr is assumed. Treated sewage sludge will be applied to the SRC plantations and one of the reasons behind the development of the scheme is in fact the search for economically and environmentally viable disposal routes for sewage sludge. Forestry residues will be mainly obtained from managed forests situated about 100 km north of the plant. The physical and chemical characteristics of wood chips from SRC willow and poplar and from forestry residues are very similar.

SRC will be planted mainly on set-aside land or on land degraded by previous agricultural, forestry or industrial uses (possible levels of contaminants in the wood will have to be carefully monitored in the latter case). Many of the activities involved in SRC plantations are typical of conventional farming activities. Crop establishment will generally require subsoiling, ploughing, harrowing, herbicide spraying, planting and fertilising activities. In the autumn prior to planting, a herbicide should be applied to control perennial weeds, and the land is ploughed. In the following spring the site is harrowed in preparation for planting, and may need fencing for protection from livestock, rabbits and deer. Planting densities range between 10,000 and 20,000 cuttings per hectare. We have assumed in this study a planting density of about 10,000 cuttings per hectare.

The cost of fencing and the price of cuttings for planting are the two major determinants of the cost of establishing SRC. In some areas existing field boundaries may be sufficient, but where fences must be built they constitute a significant cost element, typically 8% of the total delivered cost of wood chips (Ford-Robertson et al., 1993). The amenity value of rural areas and possibly biodiversity could also be affected by the choice of fencing.

Successful establishment of willow SRC, which will be mainly used for the ARBRE project, is dependent on thorough control of weeds during the establishment phase. After the first 2 years canopy closure should ensure that weed control is no longer necessary. A broad-kill herbicide such as glyphosphate ('Roundup^{TM}') is used. Studies have indicated that approximately 3kg/ha of herbicide appear as a sensible application during the first 2 years of the plantation life (ORNL/RFF, 1992; Ranney and Mann, 1994). Application would occur prior to ploughing, immediately after planting, about 6 months after planting and finally after first year cut-back. No other application should occur thereafter until replanting. No specific data is provided for the case study in question. However, a stated aim of Project ARBRE is to "...maximise the environmental benefits of this sustainable, renewable energy system" (Pitcher, 1994), and thus consideration should be given to minimisation of herbicide use.

Minimisation of herbicide use is important as herbicides may have effects on human health and other life forms via pathways such as air contamination from volatilisation during application and water contamination from leaching, runoff or soil erosion. (Ranney and Mann, 1994). Accidental spills are also a reason of concern. A US biomass fuel cycle study (ORNL/RFF, 1992) estimated that 10% of the herbicide applied could reach surface water and lead to herbicide concentrations of over 5 mg/l in some water bodies. Such concentrations could adversely affect fish fry and the larval stage of aquatic invertebrates and also human health. Impacts from herbicide application will strongly depend on agricultural practice. It is likely that no significant impacts will result from herbicide use if sensible quantities are applied and proper precautions taken in its application.

Beetles are the major threat to SRC plantations. They will colonise plantations from the borders inward and their impact can be minimised through monitoring and targeted pesticide applications. No systematic use of pesticides is expected. Rust may also require sporadic treatment although rust-resistant varieties are being marketed.

Sewage sludge will be applied to the plantations as slurry (approximately 4% solids) at establishment and then every 3 to 4 years at a rate of approximately 7 dry tonnes per hectare. Inputs of sludge are based on the nutrient requirements of the crop and will not exceed 250 kgN/ha/yr. Application will conform to EC guidelines on the application of treated sewage sludge to agricultural land (86/278/EC) (Pitcher and Lundberg, 1995). Ledin and Alriksson (1992) recommend that sludge should not be applied until the second growing season as it could coat the willow leaves, and early fertilisation might favour weeds excessively.

After 1 year of growth the plants are cut back to promote the growth of several shoots (coppicing) and the cuttings can be used as planting material in other fields. Herbicide application may occur again at this stage. This may also be a better time for the first application of sewage sludge, as the willow will be better able to compete against weeds, whose growth is also promoted by fertilisers.

The fields are harvested every 3 to 4 years. Whole shoot harvesting will be carried out, as opposed to forage harvesting directly producing wood chips. The whole shoots will be stored in bundles at the edge of the fields and left to dry. They will subsequently be chipped prior to their transport to the plant. Storage in bundles is convenient as it allows the biomass to dry, and reduces dry matter losses, fungal spore releases and the risk of fire compared to the storage of wood chips. Also, intermediary storage at the edge of the fields reduces the need for more costly storage infrastructure at the plant site. The lifetime of the plantation is expected to be 15-16 years after which grub-up occurs.

Transport to the plant site will make use of large commercial vehicles, bulk containers or articulated trailers, which will empty their load by tipping into the fuel reception area. Vehicles are likely to have a capacity of about 60 m^3. It is important to note that in the case of wood chips the limiting factor for transport is volume rather than weight.

SRC growing will have environmental impacts, however it is generally expected to be beneficial compared to the cultivation of conventional crops. For example, SRC may be beneficial in terms of reduced soil erosion rates (ORNL/RFF, 1992), enhanced biodiversity (ETSU, 1999) and increased landscape value.

Table 17 summarises the main activities of the biomass production and transport stage of the ARBRE fuel cycle and lists their consequences and relative impact categories.

Table 17: Activities and impact categories for biomass production and transport (ARBRE Plant)

Activity	Consequences	Impact category
Biomass production		
Machinery use	Air emissions	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Noise	*Rural amenity*
	Occupational hazard	*Human health*
	Fuel use	*Resource use*
	Labour requirement	*Employment*
Herbicide/pesticide use	Water pollution	Human health Ecotoxicity
	Soil pollution	Human health Ecotoxicity
Sewage sludge application	Nutrient leaching (N, P, K)	*Eutrophication impacts*
	Heavy metals (soil contamination)	*Human health* *Ecotoxicity*
	Pathogens (in air, water, soil)	*Human health*
	Odours	*Rural amenity*
Ash application	Nutrient leaching (P, K)	Eutrophication impacts
	Heavy metals (soil contamination)	Human health Ecotoxicity
	Particulates dispersion	Human health
Land use change	Soil erosion	*Soil quality*
	Landscape change	*Rural amenity* *Biodiversity*
	Water use	*Resource use*
Biomass transport	Air emissions	*Human health* *Acidification impacts* *Climate change impacts* *Ecotoxicity* (e.g. effect of ozone formation on plants)
	Road accidents from vehicle use	*Human health*
	Fuel use	*Resource use*
	Labour requirement	*Employment*
	Road use	*Rural amenity (e.g. road congestion and damage, noise)*

The biomass production activities and impact categories in the case of forest residues are assumed to be the same as those listed for the Värnamo plant in Table 12.

The developers have dedicated a lot of effort to the establishment of SRC plantations in the area surrounding the plant, but to date only a few hundred hectares of SRC have been established. The slow establishment rate of SRC plantations is likely to lead to a greater share of biomass fuel from forestry residues.

6.2 Biomass conversion

Approximately 120 odt/day of chips are to be transported in covered trucks from the fields to the plant site during its operation. The trucks, which will be weighed when entering and exiting the plant, will tip the chips into a storage building (steel clad building 15x45x12 m) which will have a capacity to store up to three days of fuel during normal operation. The fuel must be pre-treated to control size and be dried to less than 20% moisture (wet basis) in order to meet the gasification process requirements.

The dryer will be situated outside the gasification building and adjacent to it, and flue gas leaving the HRSG system will be used to dry the wood chips. The exhaust gas from the dryer will pass through particulate removal equipment and will be released to the atmosphere through a 41 m high stack. Water vapour emissions or the release of organic compounds are not expected to cause any problems. The dried wood chips are then transferred to an intermediary storage silo and subsequently to the gasifier by conveyor belts.

The gasifier is of the near-atmospheric (about 1.1 atm) air-blown circulating fluidised bed type, using sand as bed material. Low-pressure operation leads to a simpler system compared to high-pressure operation, which requires pressurised feeding and a higher degree of process control. However, the low-pressure system is likely to be a few percentage points less efficient because of the energy required for compressing the fuel gas prior to its input to the gas turbine (Bridgwater, 1995; Consonni and Larson, 1996).

The fuel gas exits the gasifier at a temperature of about 900°C and passes through a primary and secondary cyclone to remove ash, wood char and sand which are returned to the bottom of the gasifier. It then enters the tar cracker, a second circulating fluidised bed reactor similar to the gasifier reactor except that dolomite is used as a bed material instead of sand. Further partial combustion of the fuel gas will maintain the temperature of the tar cracker unit. The fuel gas then passes through another set of primary and secondary cyclones for removal of the dolomite, which is returned to the bottom of the tar cracker. It then passes through a set of gas coolers and multi-filter system baghouse filters. The coolers function as feedwater heaters and the steam raised is used in the HRSG. The baghouse filter captures residual dust from the fuel gas. The gas then goes to a wet gas scrubber in order to condense the water vapour and the majority of small hydrocarbons which would otherwise condense in the gas compressor. An acidic solution is used to scrub the gas in order to remove ammonia and other traces of alkali compounds. The fuel gas is then split into two streams, the majority of the gas going to the compressor and the remainder to the HRSG supplementary burner.

The compressed fuel gas is fired in a $4MW_e$ GEC Alsthom Typhoon type gas turbine suitable for operation on low calorific value gases. The flue gas from the gas turbine goes to the HRSG system to raise steam for a $6MW_e$ steam turbine and is finally sent to the dryer, following condensation of the water vapour, for the drying of the wood chips.

A number of ancillary equipment, known as the Balance of Plant (BoP), is required for the functioning of the plant. The BoP includes the water treatment plant, the effluent treatment plant, a chemical storage, an auxiliary fuel storage and a fire water reservoir.

The environmental statement for the plant (ARBRE, 1996a) predicts compliance of emissions with air quality standards and guidelines and states that 'in practice the emissions concentrations are likely to be less' than the requirements. A more detailed analysis of atmospheric emissions based on equipment and fuel characteristics and on experience from the Värnamo plant is provided in Section 4.1 in Chapter 5.

The biomass conversion activities and impact categories for the ARBRE plant are similar to those of the Värnamo plant and are listed in Table 15.

6.3 Waste disposal and recycling

The same considerations on waste disposal and recycling apply as for the Värnamo plant. The activities and impact categories are listed in Table 16. The uptake of heavy metals by SRC needs to be considered and is discussed in Section 4 in Chapter 5.

Table 18 provides a summary of the fuel cycle activities for the Värnamo and ARBRE plants.

Table 18: Woody biomass fuel cycles summary

	Production	Transport (On-road)	Conversion	Waste disposal
Värnamo	<u>Forestry residues:</u> Collection Chipping Transfer to roadside	Truck (90m^3) Distance: 60-90km (assumed)	HP-BIG/CC	Landfill because of testing of different biomass fuels. Forest fuel ash quality proven suitable for recycling.
ARBRE	<u>Short Rotation Coppice:</u> Herbicide treatment Subsoiling Ploughing Harrowing Planting Cutting back Fertilising (sewage sludge) Harvesting (bundle) Chipping (bundle) Rotovating <u>Forestry residues:</u> Collection Chipping Transfer to roadside	Truck (60m^3) Distance: 78-93km (based on yield, land availability, tortuosity factor)	LP-BIG/CC (Main differences between HP and LP systems: Feeding; Compression; Tar cracking; Gas clean-up.)	Recycling/Landfill. Uncertainty over ash quality.

7 The reference systems

The gasification-based biomass fuel cycles will be assessed relative to alternative means of generating heat and electricity, and reference systems need then to be defined. Coal is widely used in Sweden and the UK for thermal and electrical power generation and biomass could be used in its place, as is already the case in Sweden. Coal fuel cycles are then considered as reference fuel cycles.

Energy from coal is assumed to match the electricity output from the BIG/CC electricity generating plant in the UK and the heat output from the district heating BIG/CC plant in

Sweden where heat is considered as the main product. In the Swedish case study, the biomass gasification plant will produce electricity in excess of the coal combustion co-generation plant because of its higher power to heat ratio. The additional electricity needs to be supplied by some other source, and hydroelectricity or CCGT electricity are considered as possible sources. In the UK case study, CCGT electricity will be considered as an alternative reference fuel cycle instead of electricity from coal.

The ARBRE plant only supplies electricity and it can be readily compared to electricity from a coal power plant. Table 19 provides the energy breakdown for the Swedish reference system in order to supply the same quantity of energy as a Värnamo type plant.

Table 19: Energy breakdown for Swedish reference system

Heat from coal co-generation	0.60
Electricity from coal co-generation	0.26
Electricity from hydroelectricity or CCGT	0.14

A fluidised bed combustion plant fuelled with Polish coal and a modern pulverised coal plant fuelled with UK coal have been selected as reference coal fuel cycles for Sweden and the UK, respectively.

The Swedish coal fuel cycle is based on the Nässjo circulating fluidised bed (CFB) coal combustion plant. Table 20 provides emissions estimates for the Swedish CFB coal combustion plant. The plant generates heat and electricity and has a total efficiency of 90% (28% electrical efficiency).

Table 20: Emissions from reference Swedish CFB coal combustion plant [mg/MJ] (emissions expressed per unit of fuel energy content input to the conversion plant). (Jörgensen, et al., 1998; Gover et al., 1996 and ETSU, 1994a)

NO_x	59
CO	50
CH_4	0.3
CO_2	95800
PM	2.0
SO_2	167
NMHC	1.7
N_2O	14.0

The UK reference coal fuel cycle is based on a modern pulverised coal plant similar to the Eggborough Power Plant situated a few hundred meters from the ARBRE plant site. The Eggborough plant is a 2000 MW_e plant fuelled with coal, or when necessary, heavy fuel oil. Heavy fuel oil is used to start up the boilers and to provide additional fuel at times of peak electricity demand. The plant efficiency is close to 38%.

Table 21 provides the emissions estimates for a modern pulverised coal plant satisfying the EU Large Combustion Plant Directive (LCPD) under UK conditions (assumes 17% ash content and 1.6% sulphur content of coal). The flue gas volume rate for a coal plant is estimated to be 0.34Nm^3/MJ.

Table 21: Emissions from reference modern UK pulverised coal plant [mg/MJ] (emissions expressed per unit of fuel energy content input to the conversion plant). (Gover et al, 1996 and ETSU, 1994a)

NO_x	221.0
CO	12.2
CH_4	0.3
CO_2	88500
PM	17.0
SO_2	100.9
NMHC	1.7
N_2O	6.0

A basic description of the coal fuel cycles considered is presented in Table 22.

Table 22: Reference fuel cycle summary

Country	Supply	Conversion	Waste disposal
Sweden	Polish coal transported by rail and ship	Circulating fluidised bed (CFB) combustion	Landfill
UK	UK coal transported by rail	Pulverised fuel (PF) combustion	Landfill

The UK natural gas reference fuel cycle considers a CCGT plant fuelled with UK continental shelf natural gas transported by pipeline. Emissions typical of a CCGT plant are shown in Table 23. Emissions from the CCGT-based reference fuel cycle for Sweden are assumed to be the same as for the UK.

Table 23: Emissions from reference CCGT plant [mg/MJ] (emissions expressed per unit of fuel energy content input to the conversion plant). (Gover et al., 1996 and ETSU, 1994a)

NO_x	100.6
CO	49.0
CH_4	17.1
CO_2	50200
PM	0
SO_2	0
NMHC	1.4
N_2O	1.6

The most significant impacts from the reference systems are likely to result from the flue gas emissions at the fossil fuel conversion stage (CEC, 1995 and 1998a). The atmospheric emissions and related impacts are discussed quantitatively in Chapter 5, a qualitative discussion is provided on other possible impacts. Chapter 5 also discusses the costs of reference energy systems.

8 Conclusion

The chapter has provided an illustration of the range of resource, technical, organisational, legal and institutional factors which influence the implementation of biomass energy systems.

The first BIG/CC is being successfully demonstrated in Sweden and the ARBRE plant in the UK is to be the next BIG/CC plant to begin demonstration. Technical uncertainties are being resolved, however significant work remains to be accomplished with regard to system optimisation and economic viability. In the case of the ARBRE project, emphasis will also have to be placed on the SRC fuel logistics, on which less experience is available compared to forestry residues.

In the case of Sweden and the UK, there is still considerable biomass energy potential to be exploited, as illustrated for woody biomass and agricultural residues. Most biomass energy potential in Sweden is associated with forestry residues and estimated to range between about 34 and 195 TWh/yr. In the UK most biomass energy potential is associated with short rotation coppice and estimated to range between 33 – 166 TWh/yr. These estimates represent between 7% and 40% of current primary energy consumption in Sweden and between 1% and 6% of current primary energy consumption in the UK.

The woody and agricultural residues biomass potential could contribute between 4% and 20% of current UK electricity.

An important biomass resource is potentially available, but its exploitation requires a suitable regulatory and policy framework. Sweden is an excellent example where suitable information, demonstration and investment support programmes, and especially economic policy instruments in the form of environmental taxes and levies, have significantly contributed to the exploitation of a large potential. The UK also has shown commitment to introducing renewable energy and the main policy tool used to stimulate its market penetration has been the NFFO scheme. Although successful in many ways, in particular in its attempt at creating an initial market and stimulating the convergence of renewable energy towards prevailing market prices, the NFFO scheme is limited in its scope by the inadequate resources available and the fixed capacity targets and selected technologies for introduction. The recent consultation paper (DTI, 1999) on new and renewable energy technologies wishes to go further by setting a 10% renewable electricity target by 2010 and exploring new market stimulation measures.

The local framework is equally important for the development of biomass energy. There needs to be an awareness of the opportunities associated with renewable energy and of the local and wider benefits it may entail, as well as a provision of local plans for its exploitation.

Scattered policy initiatives have been mainly directed at overcoming economic barriers. There is though need for a more coherent and integrated approach to policies covering agriculture, energy and the environment. Adequate economic instruments taking into consideration the social costs and benefits of different fuel cycles are fundamental. They will however not suffice in promoting renewable energy, biomass in particular. Efforts need to be made in disseminating information on the possibilities of exploiting biomass energy, an issue of particular importance because of the diverse nature of biomass energy and because of the different sectors and key players which may be involved.

Biomass fuel cycles may be relatively complex in terms of the players involved. In particular, fuel procurement may involve a number of different players and may vary considerably in terms of fuel production and transport logistics as well as arrangements between the different players. In Sweden, there is good experience with forest fuels and a market for wood fuels has developed. In the UK, where biomass energy is to rely largely on wood chips from short rotation coppice, experience in the production and transport of such biomass fuel is limited. Farmer's attitudes will be determining in the success of energy crops, and suitable arrangements need to be found between the plant developers and the fuel producers. Lack of information on energy crops, and biomass energy in general, and uncertainties on the future of agricultural policies act as barriers to the introduction of energy crops. The trend away from supporting farmers through subsidies to traditional food crops is likely to lead to a more level playing field between different agricultural products, which may favour energy crops. Furthermore, SRC could receive support in its own right as part of a more sustainable agricultural and energy policy. A favourable regulatory and policy climate which allows to reap the possible benefits of renewable energy systems will spur the entry on the market of biomass plant developers, which can range from utilities to independent power producers to industry (e.g. agro-industry). Issues related to fuel procurement may deter plant developers, and much can be learned from the ARBRE plant in this respect. Information directed at key players and the public is of fundamental importance.

The discussion of the regional context provides an indication of the possible benefits of biomass energy. For example, the displacement of coal for district heating by biomass in Sweden is believed to present benefits in terms of air quality and acidification. Similar considerations apply to the displacement of conventional generation by biomass energy in the UK, although specific siting issues related to energy crops need to be considered. Regional information is fundamental in identifying potentially significant impacts of biomass fuel cycles (e.g. presence of NVZs, high background pollution levels, landscape issues, etc.). Land availability also needs to be addressed in the case of SRC. Employment is an important issue at the local and regional level, and the economic diversification and the employment resulting from biomass energy schemes in rural areas are likely to be highly desirable.

The detailed description of the fuel cycles emphasises technical uncertainties and aspects requiring particular attention. It also provides key information for the economic and environmental analysis presented in Chapter 5. While there is considerable experience with forest fuel logistics in Sweden, experience needs to be acquired on the logistics of biomass fuel from SRC in the UK. The fuel cycles present no major technical barriers, but some particular activities may present problems or could be improved, such as storage (e.g. decomposition, fire hazards, flow problems), pre-treatment (e.g. biomass drying, problems with condensate), feeding (e.g. blockages), gas quality and cleaning, operation of the integrated system, ash recycling.

The discussion on the fuel cycles has identified the priority impact categories. In the case of the biomass fuel cycles considered they are: human health, acidification impacts, eutrophication impacts, climate change impacts, ecotoxicity, soil quality, rural amenity, biodiversity and resource use.

The following chapter provides a detailed economic, environmental and resource use analysis of the Värnamo and ARBRE type biomass fuel cycles and assesses them in relation to the reference systems described above.

CHAPTER 5

ECONOMIC, ENVIRONMENTAL AND RESOURCE USE ANALYSIS OF THE SWEDISH AND UK CASE STUDIES

1 Introduction

The scope of this chapter is to provide a detailed economic, environmental and resource use analysis of the Värnamo and ARBRE fuel cycles and to extend it to the short-term development of similar fuel cycles. The economic, environmental and resource use performance of the gasification-based biomass fuel cycles is assessed relative to the reference systems defined in Chapter 4. The quantitative results presented are based on a spreadsheet database and model developed to calculate the private costs (base year 1995), employment, emissions and non-renewable energy use inventories associated with the biomass and reference systems (see Annex 1 for details).

2 Economic analysis

The economic analysis consists of a detailed analysis of the private costs of the different stages of the Värnamo and ARBRE fuel cycles and of the cost of the electricity and heat generated.

2.1 Private costs analysis

Details of the cost calculations are provided in Annex 1. The calculations are influenced by assumptions regarding fuel mix, activities inventories (e.g. materials, machinery, work period required for SRC activities), transport distances, equipment and processes involved in the conversion stage, and ash disposal options. A 5% discount rate has been applied in calculating discounted cash flows in the case of the Värnamo and ARBRE case studies. The analysis provides cost estimates for gasification-based biomass fuel cycles for heat and electricity in the short-term, based on discount rates of 5%, 10% and 15%, and discusses the parameters significantly affecting the fuel cycle costs.

2.2 Biomass fuel production costs

The biomass fuel used in the Värnamo Power Plant is assumed to be 100% forest residues. The fuel production cost (Table 24) has been calculated using a forestry activities inventory for Sweden based on materials and machinery use and activity times.

The biomass fuel used for the ARBRE plant is assumed to consist of 80% SRC and 20% forestry residues. The cost of the production of biomass fuel from SRC is calculated using a detailed UK based activities inventory for the production of wood chips from SRC. The production of wood chips from forestry residues is based on the activities inventory for Sweden, modified for UK costs for materials and labour inputs.

Details of the costs can be found in Annex 1. Table 24 gives the cost ranges calculated for the production of the biomass fuels, and Figure 9 and Figure 10 provide a breakdown of the costs. These costs define the baseline biomass fuel costs for the case studies.

Table 24: Biomass fuel production costs

Facility	Biomass fuel	Cost [€/GJ]		
		Mid-range	Min.	Max.
Värnamo*	Forestry residues (chips)	2.12	1.55	2.69
ARBRE	SRC (chips)**	2.00	1.09	2.91
	Forestry residues (chips)	2.10	1.52	2.69
	Biomass fuel mix	2.02	1.17	2.87

* the Värnamo plant may also use wood wastes from sawmills, according to availability, at a cost lower than that of forestry residues - this option has not been considered, the influence of lower costs will be assessed in the sensitivity analysis.

** the costs account for the use of sewage sludge for fertilisation/irrigation, though the transport of sewage sludge is considered to lie outside the boundaries of the system considered.

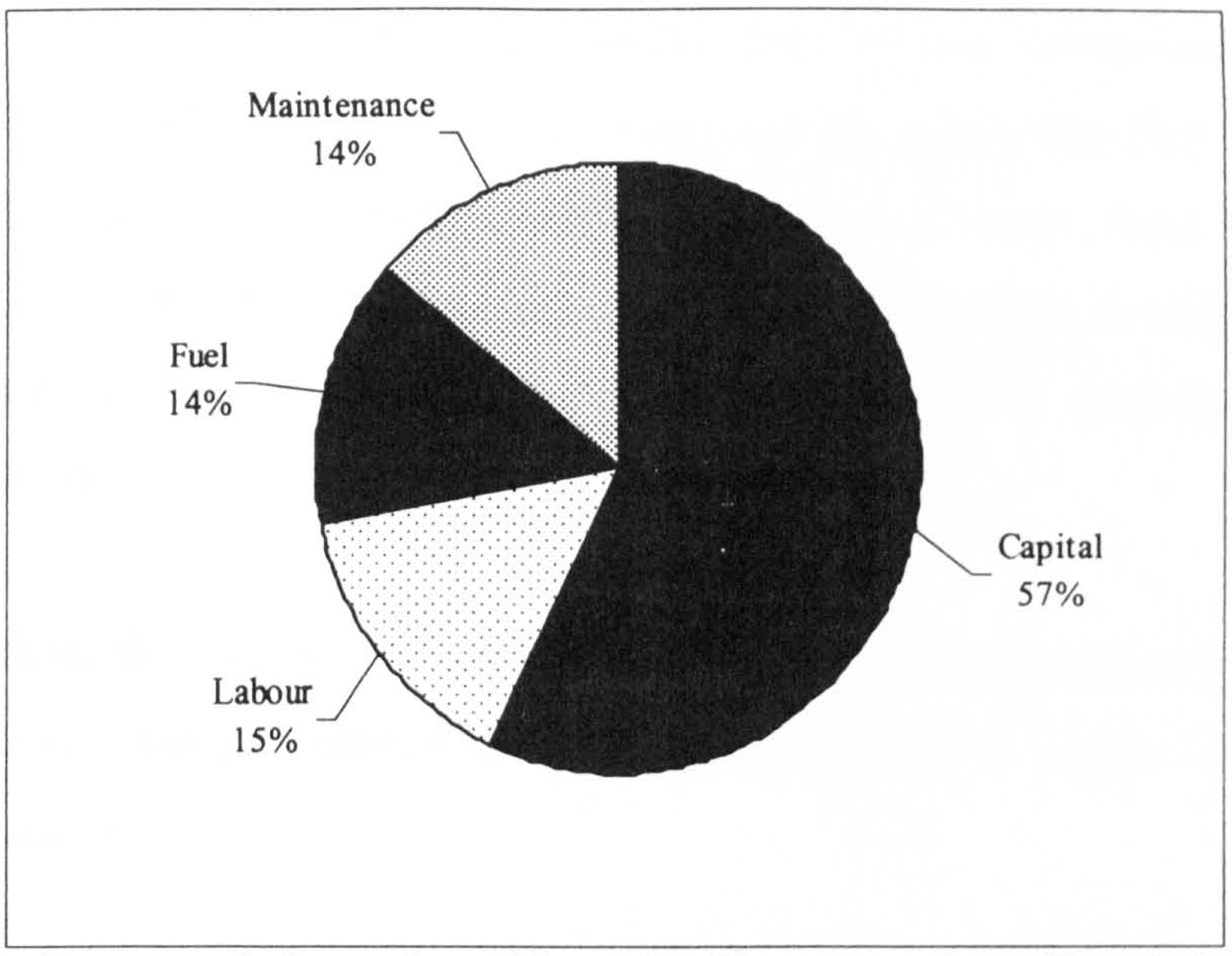

Figure 9: Biomass fuel cost breakdown for Värnamo plant (Total: 2.12 €/GJ)

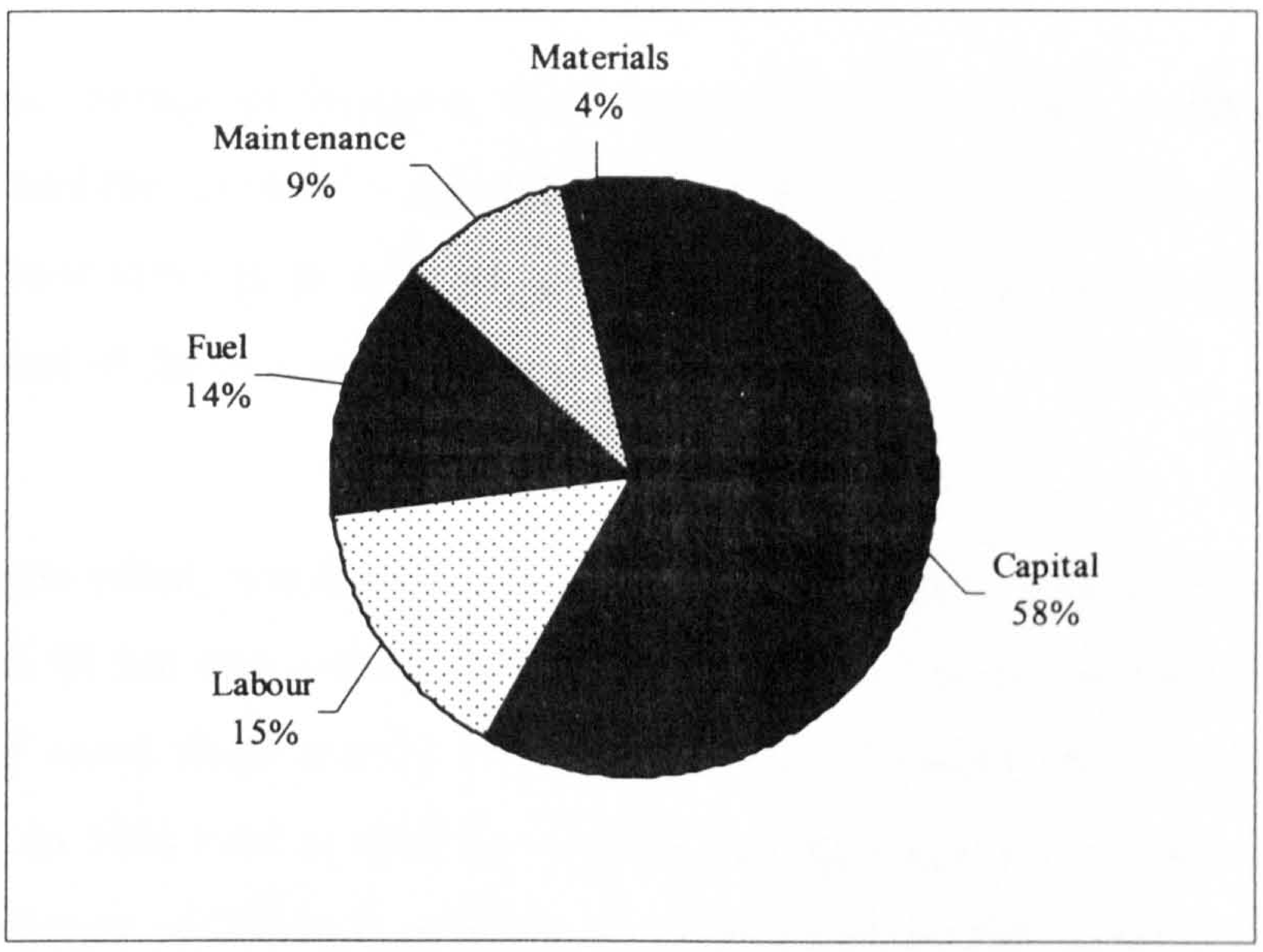

Figure 10: Biomass fuel cost breakdown for ARBRE plant (Total: 2.02 €/GJ)

The application of sewage sludge results in a 1 - 4% reduction in the cost of biomass fuel from SRC compared to the case where no sewage sludge is applied and inorganic fertilisers are used. This cost reduction accounts exclusively for the reduction in input of chemical fertilisers. No additional cost or disposal credit is assumed to result from the application of sewage sludge.

Fencing costs, incurred to protect the crop from animals such as rabbits and deer, have not been included in the above cost of biomass fuel production from SRC. These will vary for different plantations and may not always be required. Assuming that fencing costs add about 20% to the establishment costs would result in a 10% increase in the cost of fuel. Also, the costs above do not account for any administration costs or margins related to profit and risk. These may increase the cost of the fuel by up to about 20%. Subsidies and taxes may further influence the cost of the biomass fuel, but these have not been considered in the calculations. Biomass fuel costs vary geographically since they are a function of geographically dependent variables such as labour costs, fossil fuel costs, etc.

Biomass fuel from forestry residues and from SRC can be produced at similar cost for the UK case study, and the costs of biomass fuel appears to be similar for the UK and Swedish case studies.

2.3 Biomass fuel transport costs

No intermediate storage of biomass fuel occurs between storage at the harvesting or collection site and the short-term storage at the plant. The only storage costs considered are therefore those at the plant and they are accounted for in the conversion costs as part of the capital cost of the conversion facility.

For the Värnamo plant, wood chip transport costs assume a return transport distance between 60 and 90 km and a truck capacity of 90 m^3. In the case of the ARBRE plant, the transport of wood chips assumes a return distance between 48 and 66 km for SRC, based on a 5% to 10% land availability around the plant and a road tortuosity factor of 1.3, a return distance of 200 km for forestry residues and a truck capacity of 60 m^3. The transport costs are calculated on the basis of typical contractor costs per kilometre provided for Sweden and the UK, including loading and unloading costs (see Annex 1). The costs are summarised in Table 25. The significant transport distance required for the supply of wood chips from forestry residues to the ARBRE plant results in a very high transport cost.

Table 25: Biomass fuel transportation costs

Facility	Biomass fuel	Cost [€/GJ]		
		Mid-range	Min.	Max.
Värnamo	Forestry residues (chips)	0.42	0.26	0.59
ARBRE	SRC (chips)	0.32	0.21	0.42
	Forestry residues (chips)	1.08	0.90	1.26
	Biomass fuel mix	0.46	0.35	0.59

2.4 Comparison of biomass and reference fuel costs

The total costs of biomass fuel delivered to the plant are shown in Table 26 for the Värnamo and ARBRE plants.

Table 26: Biomass fuel cost at plant gate

Facility	Biomass fuel	Cost [€/GJ]		
		Mid-range	Min.	Max.
Värnamo	Forestry residues (chips)	2.54	1.81	3.28
ARBRE	SRC (chips)	2.32	1.30	3.33
	Forestry residues (chips)	3.18	2.42	3.95
	Biofuel mix	2.49	1.52	3.46

As a comparison, Table 27 shows the fossil fuel costs for the reference fuel cycles.

Table 27: Reference fossil fuel costs (IEA, 1996)

Facility	Cost [€/GJ]
Coal - Sweden	1.59
Coal - UK	1.80
Gas - UK	2.15

2.5 Biomass conversion cost and cost of electricity and heat generated

The BIG/CC plant investment costs have been calculated based on a detailed breakdown of plant equipment, design, construction and installation costs (see Annex 1). The total cost of the Värnamo plant is estimated at €28 million and that of the ARBRE plant at €31 million. These costs translate to specific installed power costs of €4,700/kW$_e$ and €3,900/kW$_e$, respectively. The operation and maintenance (O&M) costs are composed of the biomass fuel and other materials costs (at the plant gate), maintenance costs, ash disposal costs and overheads. Table 28 provides the total private cost of the energy produced by the biomass fuel cycles considered allocated by energy. Figure 11 to Figure 14 provide a breakdown of the investment and O&M costs. Allocation does not affect the cost of energy in the case of the ARBRE plant since electricity only is generated, but it does affect the cost of heat and electricity for the Värnamo plant. In reality, cost allocation will be influenced by exogenous factors such as the cost of producing heat and electricity from alternative sources or the price at which the products can be sold on the market. For example, if electricity could be sold to an electricity pool for €30/MWh then heat would at least have to be sold at a price of €68/MWh to recover the costs.

Table 28: Investment, O&M and generation costs allocated on an energy basis

Facility	Cost category	Cost [m€/kWh]*		
		Mid-range	Min.**	Max.
Värnamo	Investment	34.5	37.2	31.8
	O&M	18.2	14.4	22.0
	Total private cost	*52.7*	*51.6*	*53.8*
ARBRE	Investment	41.8	41.8	41.8
	O&M	38.1	26.2	50.0
	Total private cost	*79.9*	*68.0*	*91.8*

*costs are expressed per unit of useful energy (electricity and heat)

**investment min and max values have been interchanged because a higher investment leads to a higher degree of plant automation and consequently to a lower O&M cost and a lower total private cost (and vice-versa)

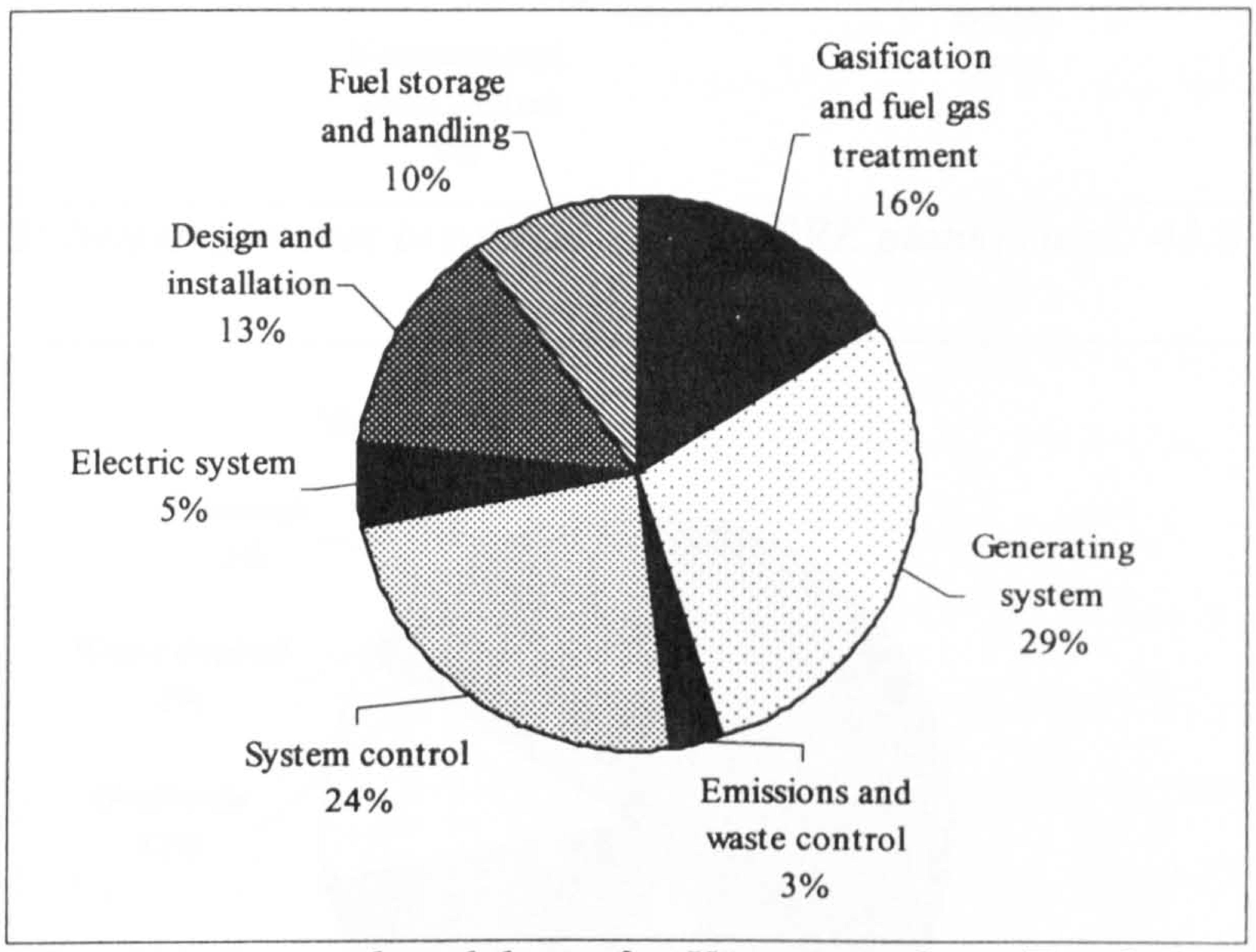

Figure 11: Investment cost breakdown for Värnamo plant (Total: 34.5 m€/kWh)

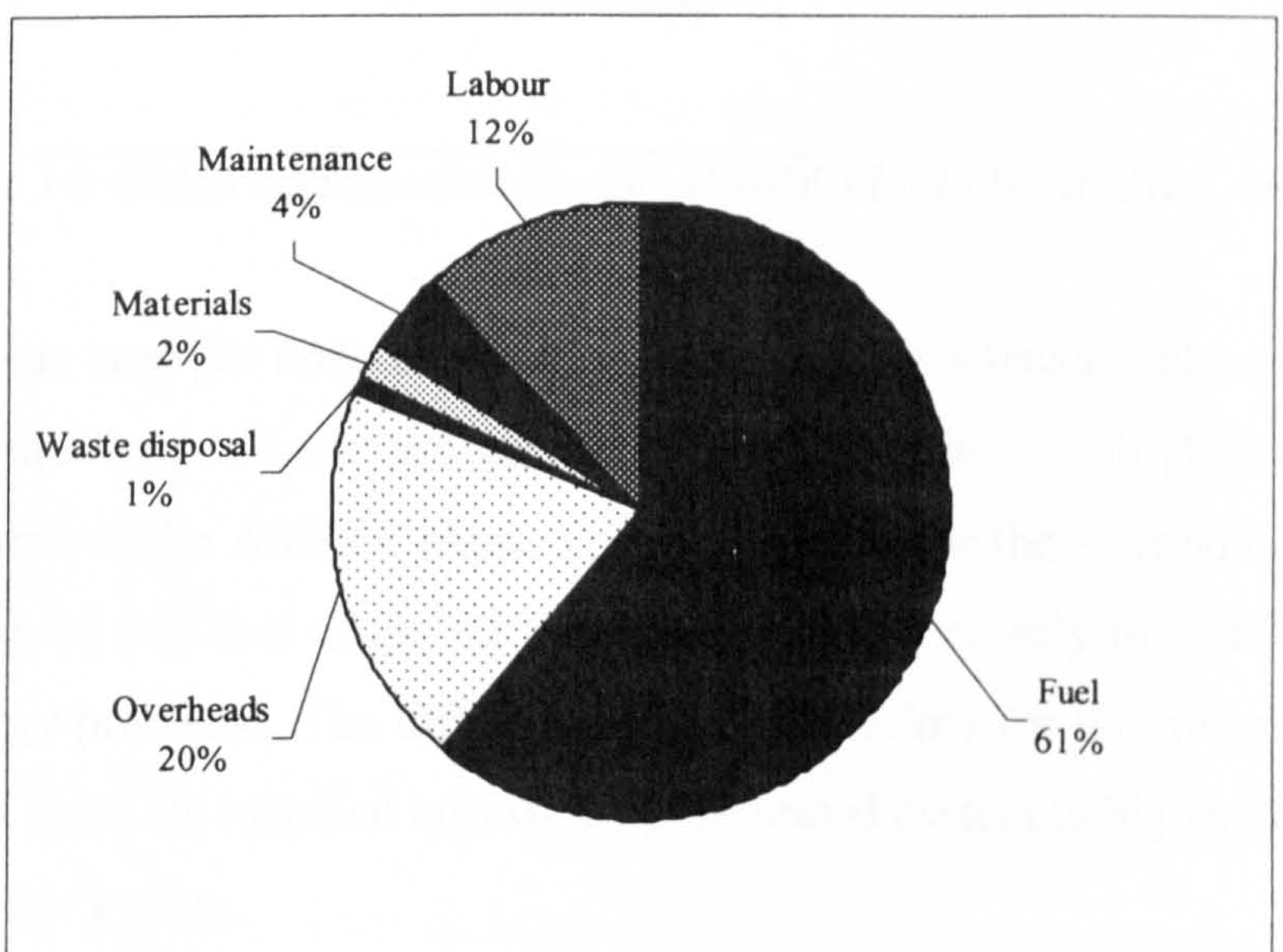

Figure 12: O&M cost breakdown for Värnamo plant (Total: 18.2 m€/kWh)

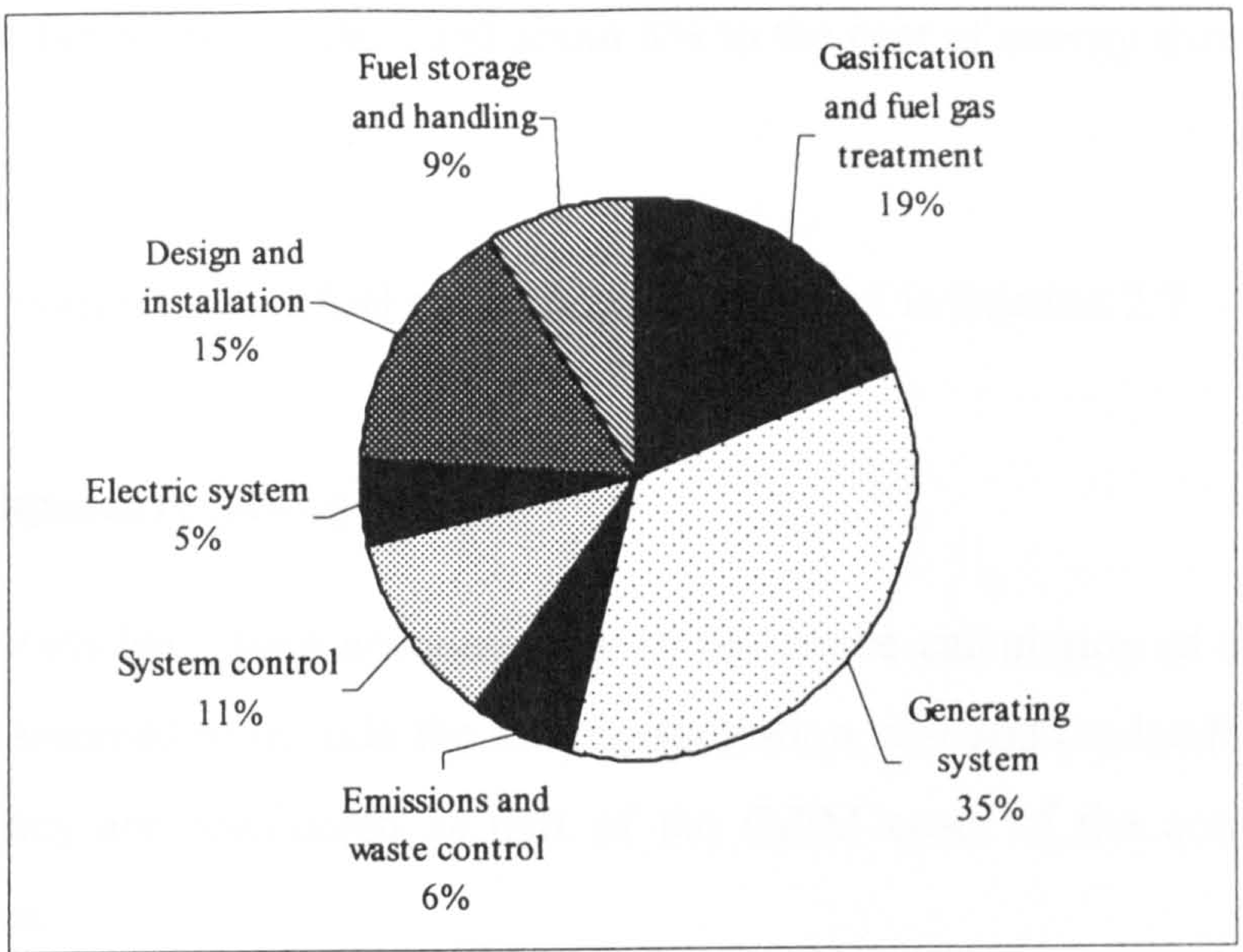

Figure 13: Investment cost breakdown for ARBRE plant (Total: 41.8 m€/kWh)

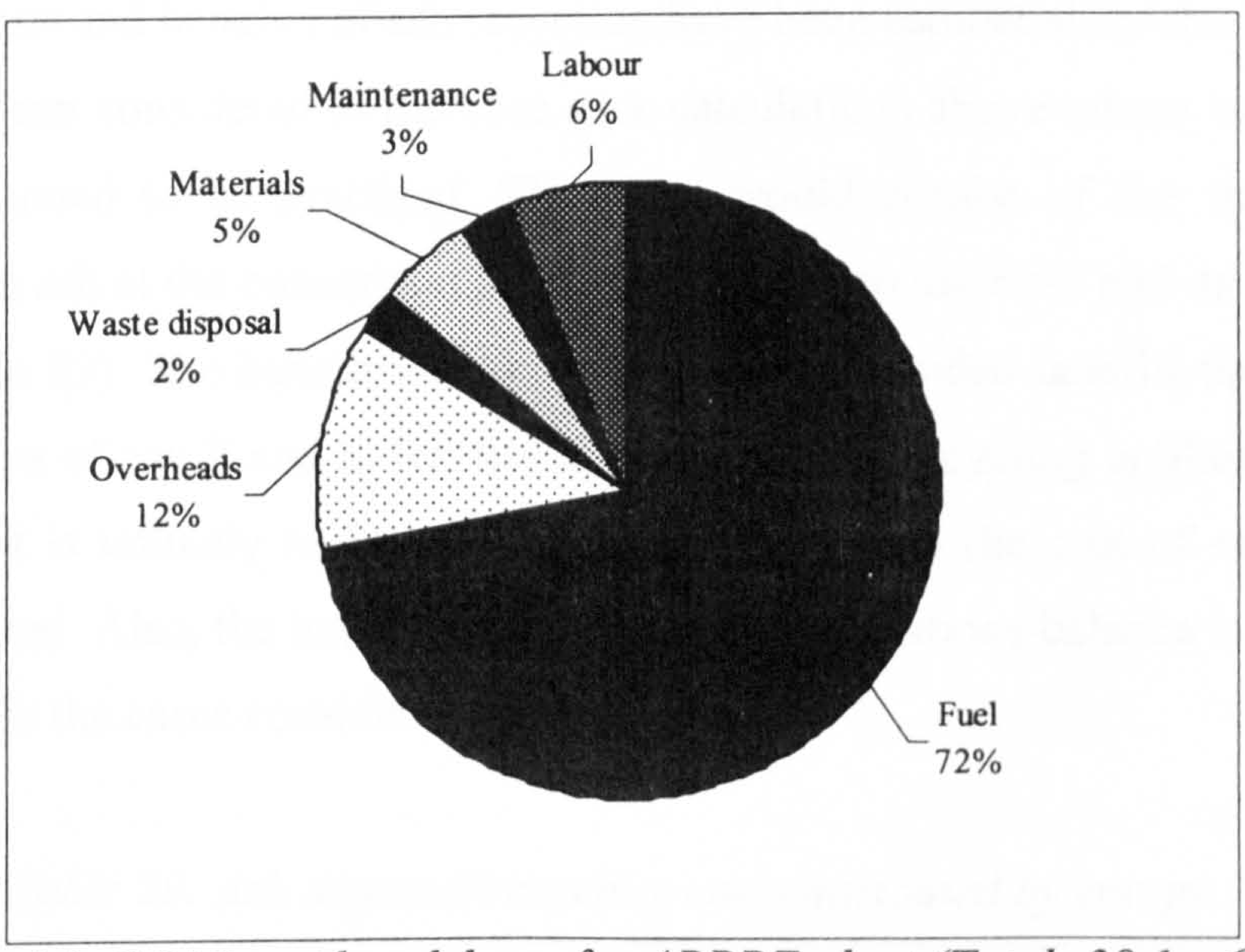

Figure 14: O&M cost breakdown for ARBRE plant (Total: 38.1 m€/kWh)

The total private cost per unit of energy is lower for the Värnamo plant because of its combined production of heat and electricity which leads to a higher useful energy output compared to the ARBRE plant. The O&M costs for the Värnamo plant per unit of energy is about half that of the ARBRE plant and this closely reflects the difference in useful energy produced. The difference is not so marked for the investment cost per unit of energy since the installed cost of the pressurised system is higher than that of the near-atmospheric system.

The consideration of fencing costs, administrative costs and profit and risk margins on top of the costs provided in Table 24 (see section 2.2), would add about 4% to the cost of energy from the Värnamo plant and about 8% to the cost of energy from the ARBRE plant.

A comparison with reference fuel cycles costs is provided in Section 2.7.

2.6 Ash disposal/recycling costs

Ash disposal costs have been accounted for in the above calculation of the generating costs, and are assumed to include the ash transportation cost and the landfill tipping fee (Table 29). They are considered as part of the O&M costs of the conversion stage discussed above.

The private costs and benefits of ash recycling have been estimated for the Swedish case but have not been considered in the base case calculations above where ash disposal to landfill is assumed to be practised. The costs would consist of the stabilising and crushing of the ash at the conversion plant, its transport to the field and its spreading on the field (Table 29). The benefit would result from the avoided landfill tipping fee and the avoided cost of any P and K fertilisers. Although ash recycling is likely to result in cost savings, it is unlikely to have a significant impact on the cost of energy for the plants considered. Also, the impact on the energy and emissions balance is not likely to be significant in the cases considered.

Table 29: Ash disposal/recycling costs attributed by energy

Facility	Cost* (m€/kWh)		
	Mid-range	Min.	Max.
Värnamo			
Disposal	0.26	0.11	0.40
Recycling	0.29	0.19	0.40
ARBRE			
Disposal	0.76	0.54	0.98

* the transportation distance and capacity are assumed to be the same as those for biomass fuel transport

2.7 Electricity and heat generation costs: sensitivity and projections

The detailed cost calculations for the demonstration projects provide useful insight into the current cost components of activities involved in biomass production, transport and conversion, the influence of the different stages of the fuel cycle on the cost of energy, and areas where cost reductions could and should be achieved.

The cost of energy generation from the demonstration biomass fuel cycles studied are high and significantly higher compared to those of conventional fuel cycles. The high costs are largely due to the demonstration nature of the biomass fuel cycles and cost reductions would undoubtedly result from improvements in the fuel cycle, economies of scale and replication, for all stages of the fuel cycle, in particular the conversion stage. To compare the cost of energy from the biomass demonstration plants with the costs of energy from the reference systems would not reflect the true potential of BIG/CC systems. Therefore, an indicative comparison of costs is provided which takes into consideration cost reductions which could be achieved by short-term developments.

The cost of biomass fuel delivered to the plant is significantly higher than that of the reference fuels considered (coal and gas). Thus, reductions in biomass fuel costs are necessary in order for it to become more competitive. There is scope for greater efficiency in biomass production and for cost reductions, for example in relation to machinery costs. The exogenous parameters which have a significant influence on the cost of the biomass fuels considered are the costs of diesel, machinery, labour and transport (the latter is determined by specific contractor costs and distance travelled). The endogenous parameters of significance are SRC yield and the activity times involved in the production of the biomass fuels. Small changes in the efficiency of biomass operations is not likely to have a significant effect on the cost of biomass fuel, and the range of activity times used for the case studies are believed to reflect relatively efficient operations. The biomass fuel cost sensitivity to variations in the mentioned parameters is illustrated in Figure 15 and Figure 16 for the case of the Värnamo and ARBRE case studies.

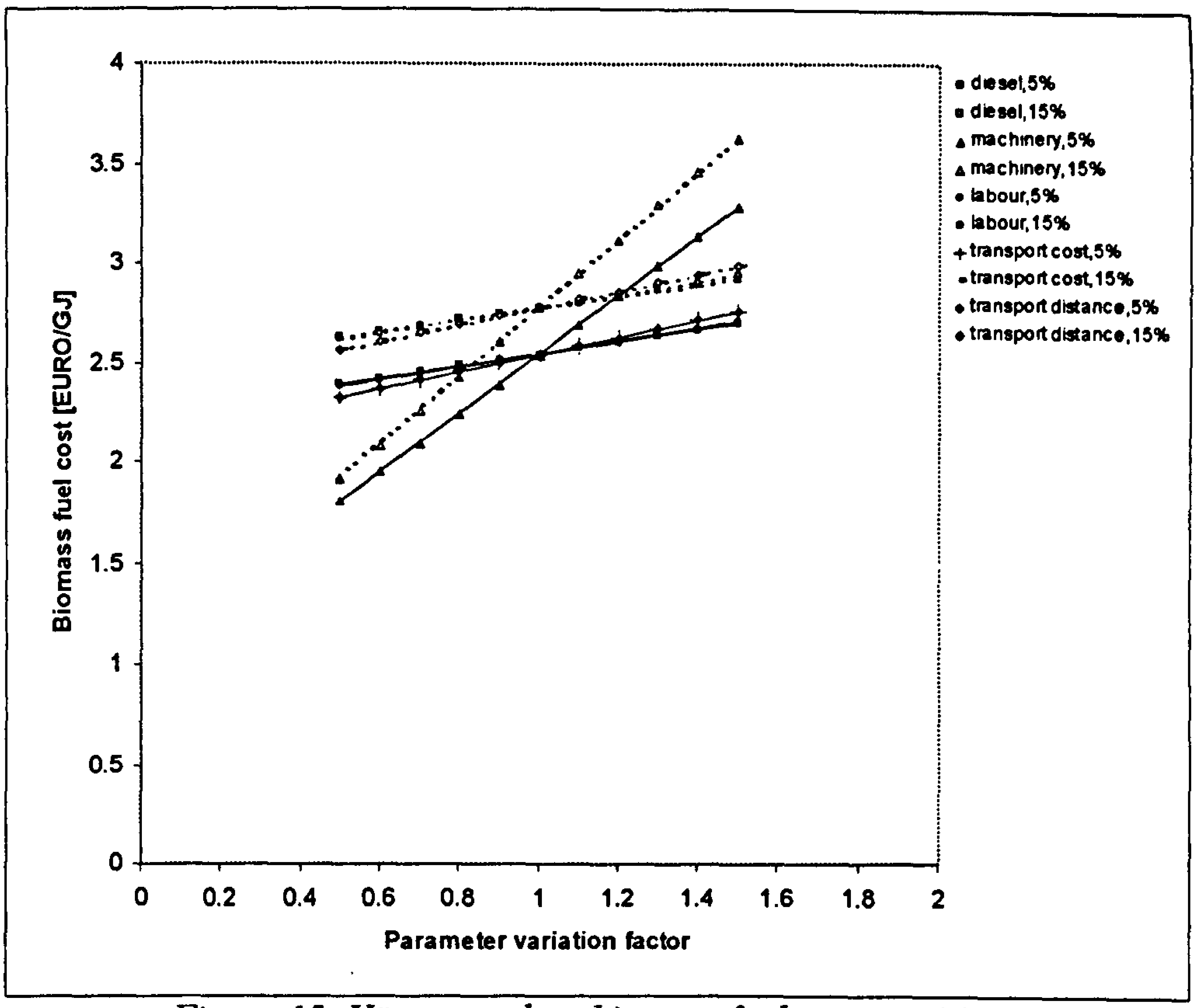

Figure 15: Värnamo plant biomass fuel cost sensitivity

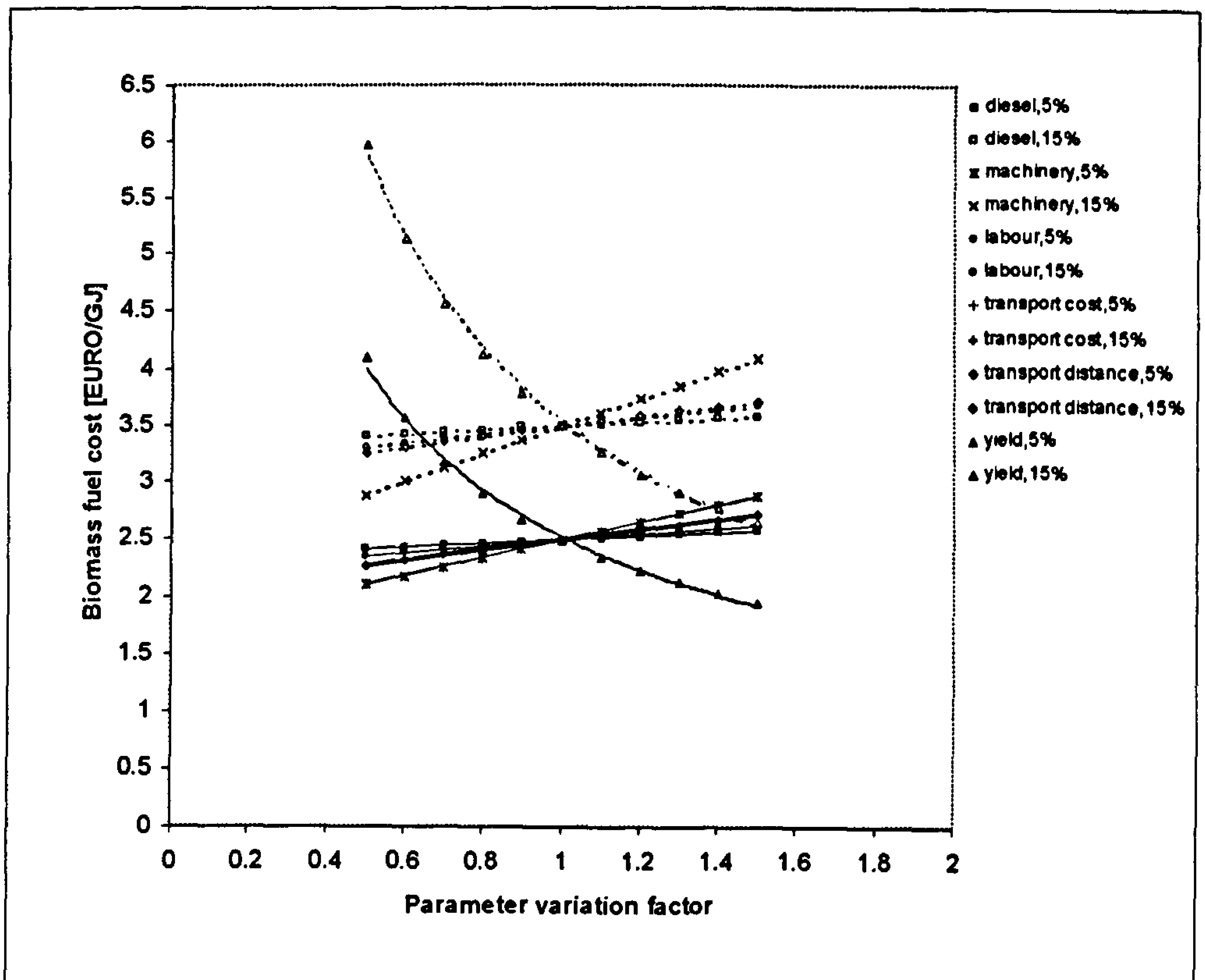

Figure 16: ARBRE plant biomass fuel cost sensitivity

In the case of SRC, yield is the parameter affecting the most the biomass fuel cost. The exogenous parameter which bears greatest influence on the biomass fuel costs is the cost of machinery. Machinery cost reductions should result as the biomass industry develops. Transport cost is the other exogenous parameter with most influence on the cost of biomass fuels. Reductions in specific transport contractor costs may result from increased competition, as has been the case in Sweden. The influence of transport distance is also significant and biomass fuel procurement logistics should aim to minimise it. Variations in diesel and labour costs are those with least influence on the biomass fuel costs. Based on the sensitivity analysis and on likely short-term variations in the values of the parameters considered, a 10-20% reduction in biomass fuel costs appears reasonable in the short term. Reductions in costs for wood chips derived from forestry residues are likely to be lower than for those derived from SRC because of the SRC potential for cost reductions associated with increases in yields.

Economies of scale and replication are likely to significantly influence biomass conversion costs. Figure 17 and Figure 18 illustrate the estimated variation of investment costs in the conversion stage as a function of electricity generation capacity, including an estimated short-term reduction in costs of 20% as a result of 'learning by doing'. The calculations are based on conversion plant scaling factors discussed in Annex 1.

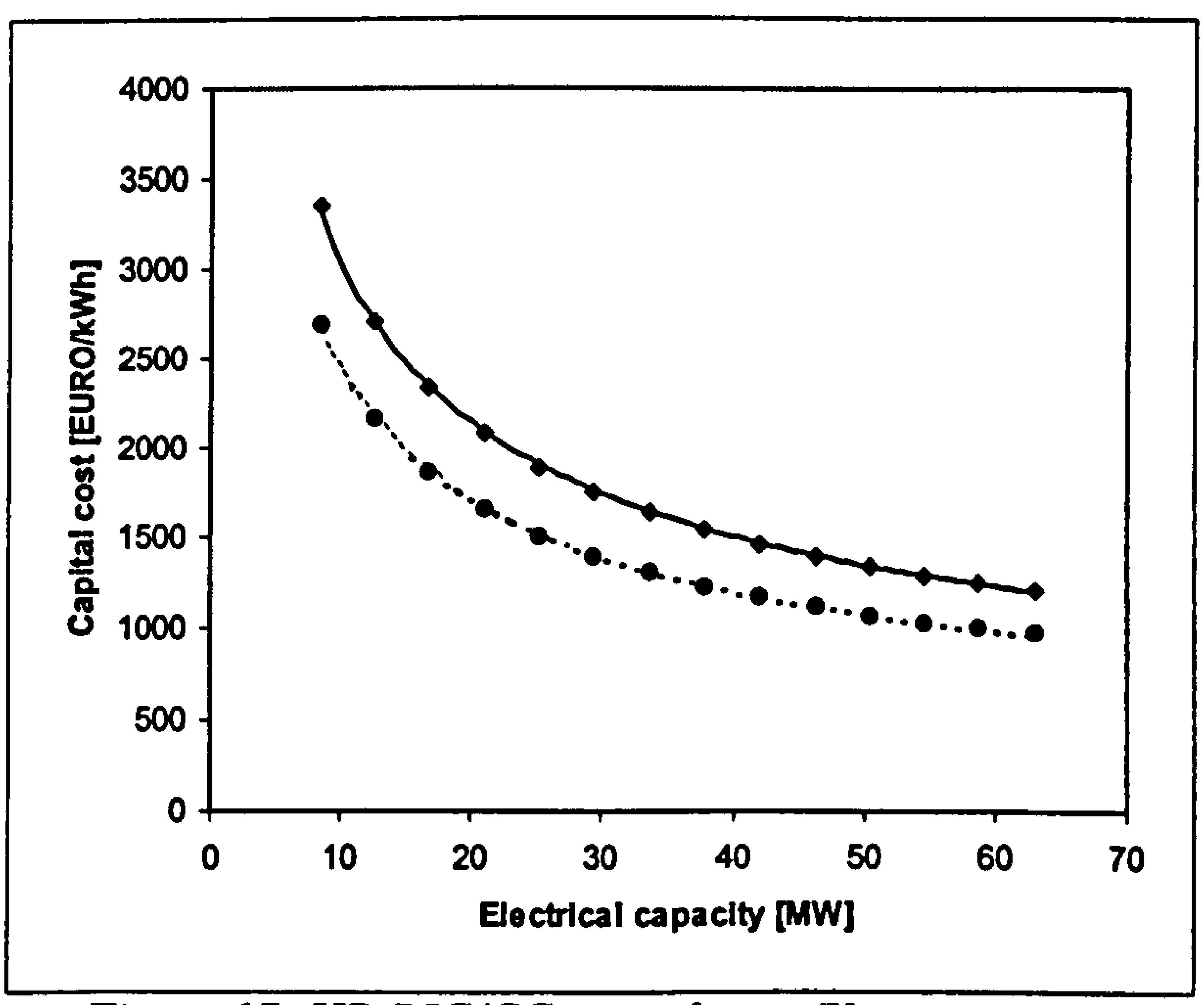

Figure 17: HP-BIG/CC capital cost (Värnamo type)

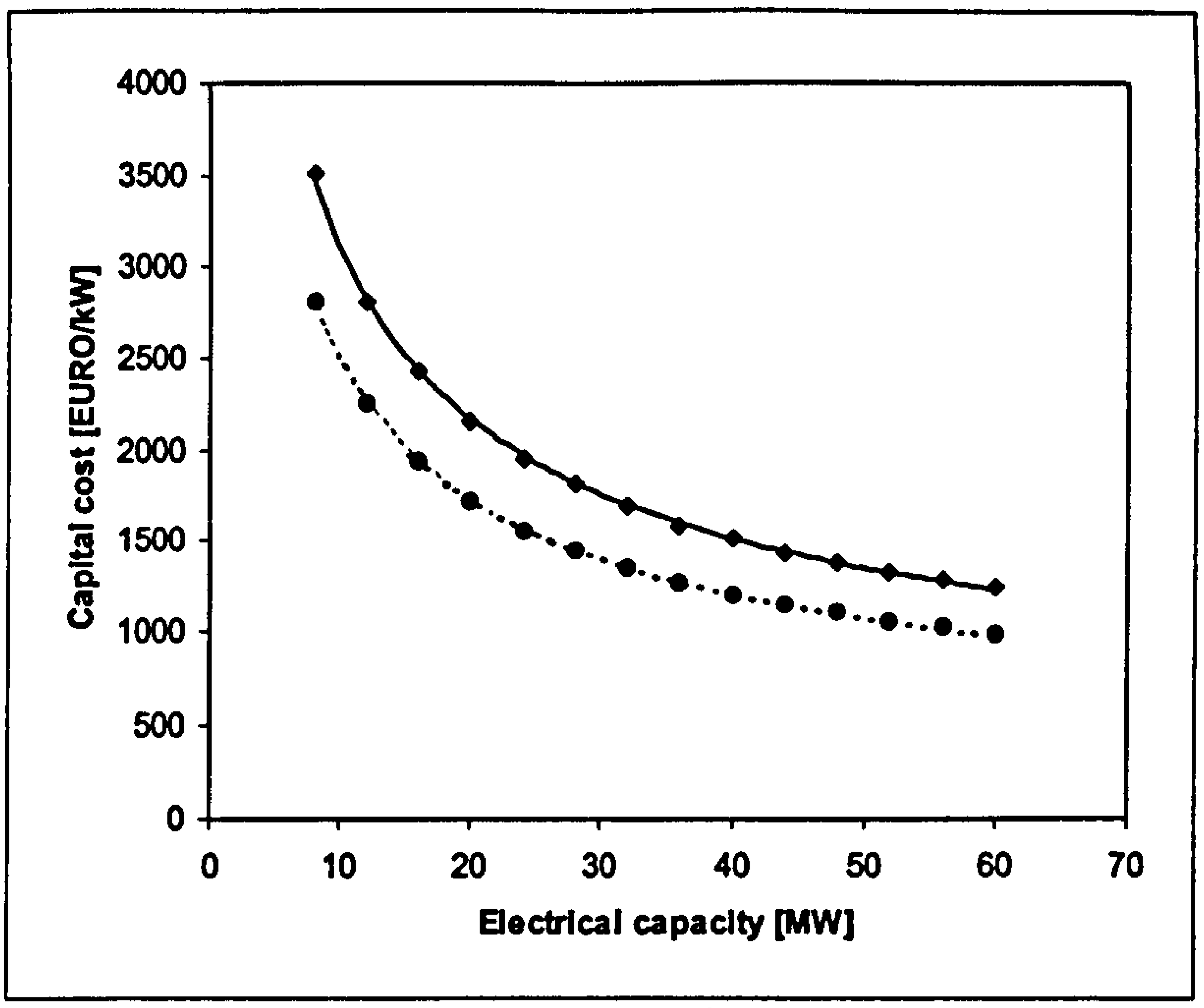

Figure 18: LP-BIG/CC capital cost (ARBRE type)

Based on the above cost sensitivity and reduction considerations, the potential short-term cost projections are estimated for plants of the same type as the demonstration plants studied. Figure 19 and Figure 20 provide cost projections for Värnamo and ARBRE type plants as a function of electrical capacity and discount rate applied. The efficiencies of the LP and HP-BIG/CC conversion plants are estimated at 40% and 45%, respectively. In the case of co-generation, the total (heat and electricity) plant efficiency is estimated at 85%. The power to heat ratio is likely to be slightly greater than one.

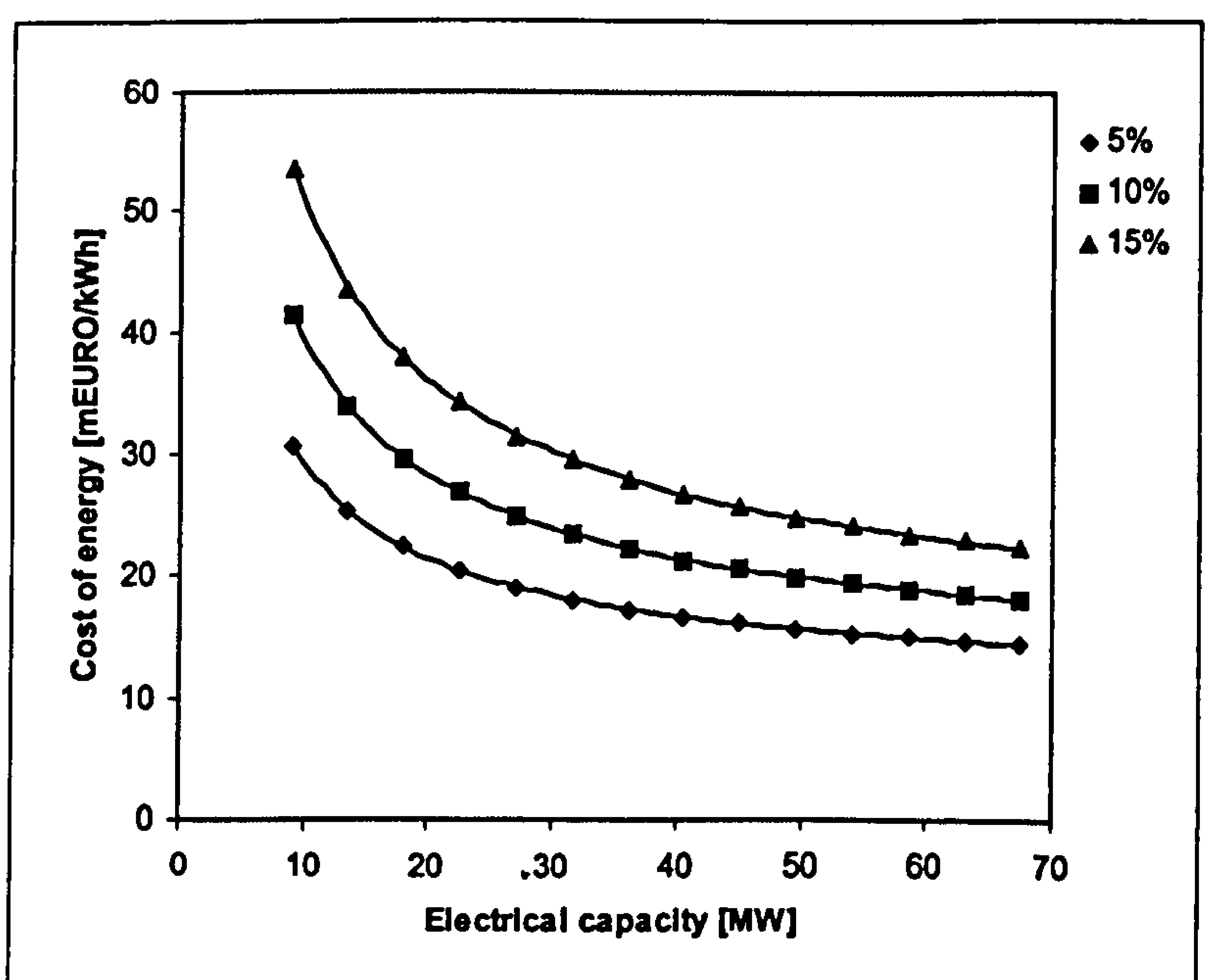

Figure 19: Cost of energy for Värnamo type plant

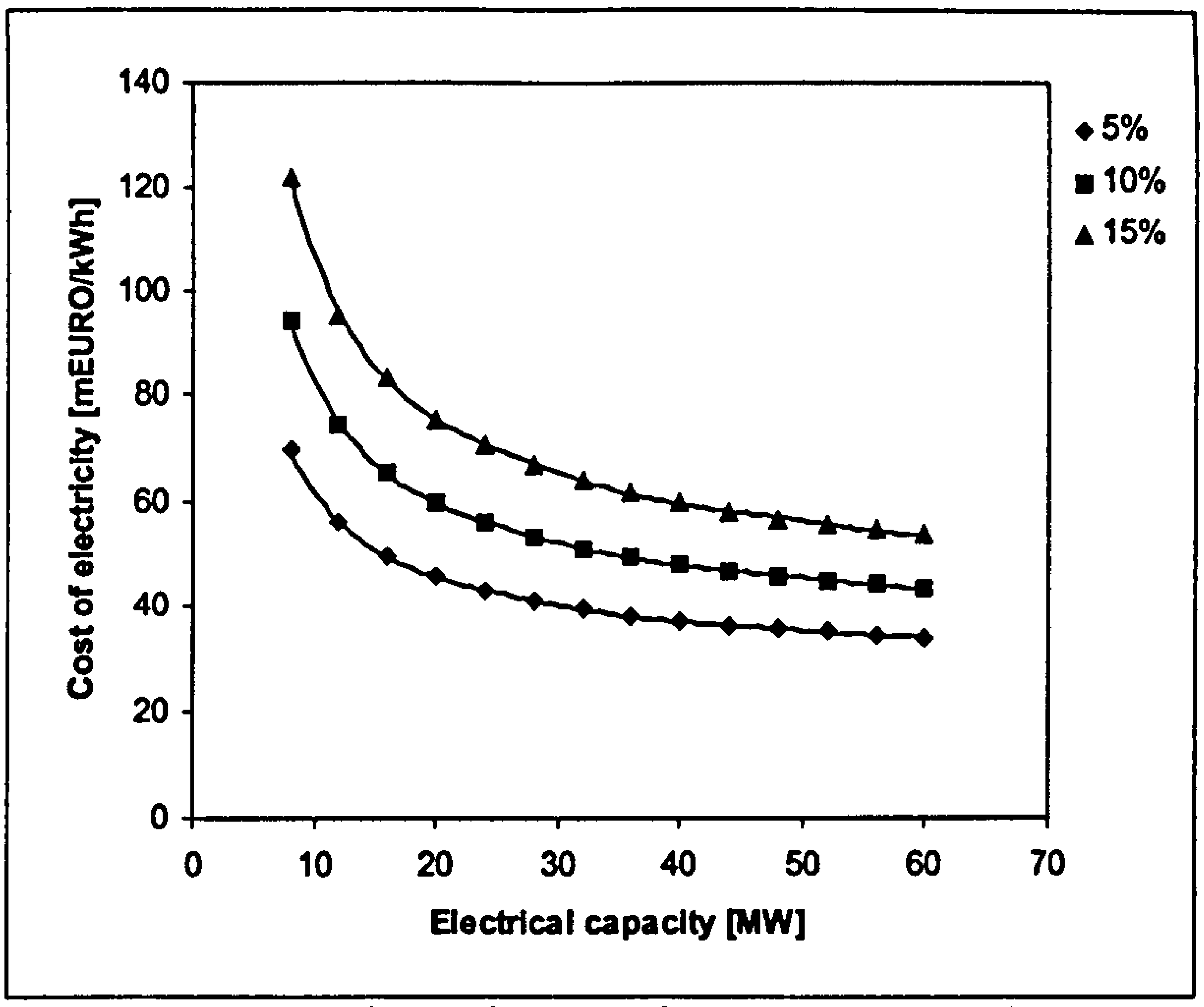

Figure 20: Cost of energy for ARBRE type plant

Figure 21 illustrates the sensitivity of the cost of electricity to the biomass fuel cost, the generating plant capital cost and its variable costs other than fuel cost for a 30 MW_e generating plant. The cost of electricity shows a similar sensitivity to biomass fuel cost and to capital cost. A 20% reduction in the cost of either biomass fuel or capital cost results in about a 10% reduction in the cost of electricity.

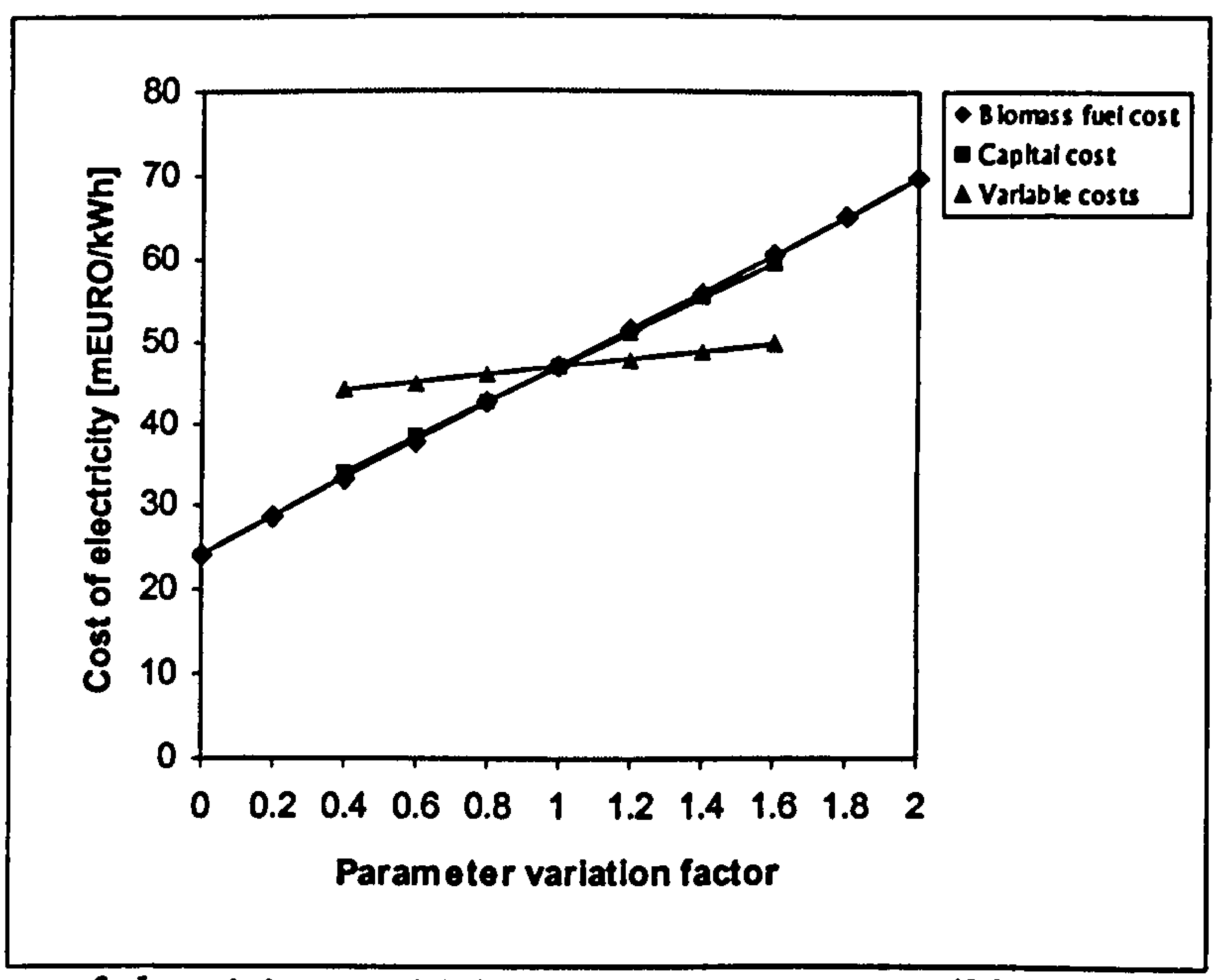

Figure 21: Cost of electricity sensitivity (30 MW_e LP-BIG/CC, 10% discount rate, base case fuel delivered to the plant cost: €2.53/GJ)

As a comparison, the cost of energy (heat and electricity allocated on an energy basis) for the Swedish reference coal fuel cycle and the cost of electricity for the UK coal and natural gas reference fuel cycles are shown in Table 30.

Table 30: Cost of energy for reference fuel cycles for different discount rates

	Cost of energy [m€/kWh]		
	5%	*10%*	*15%*
Coal cogen. Sweden[1]	25.0	31.0	37.9
Coal UK[2]	33.7	38.5	44.0
CCGT UK[3]	23.8	25.9	28.3

[1] Assumes investment cost of €2180/kW, fixed annual operating cost of €69/kW (Jörgensen et al., 1998), coal cost of €1.59/GJ, lifetime of 20 years
[2] Assumes investment cost of €965/kW, fixed annual operating cost of €31/kW (ETSU, 1994a), coal cost of €1.80/GJ, lifetime of 20 years
[3] Assumes investment cost of €422/kW, fixed annual operating cost of €18/kW (ETSU, 1994a), gas cost of €2.15/GJ, lifetime of 20 years

The average annual price of electricity in Sweden in 1997 for households was SEK0.773/kWh (m€88.9/kWh), of which tax represents SEK0.281/kWh (m€32.3/kWh) consisting of SEK0.126/kWh (m€14.5/kWh) excise tax plus SEK0.155/kWh (m€17.8/kWh) VAT. The price of electricity for industry was SEK0.261/kWh (m€30.0/kWh). The average annual district heat price in 1997 was SEK0.427/kWh (m€49.1/kWh), including 25% VAT. The average annual price of electricity in the UK in 1997 was £0.0714/kWh (m€103/kWh) for households and £0.0395/kWh (m€57.2/kWh) for industry (IEA, 1999b).

The reduction of the private costs of the biomass systems is an issue of key importance. The actual cost of energy from the Värnamo and ARBRE plant is high because of the demonstration nature of the plants and the commercial infancy of the technology. Economies of scale and assumptions on reductions in the fuel costs and conversion stage investment costs can lead to significant cost reductions in the energy produced by BIG/CC systems in the short-term. The short-term cost estimates indicate that BIG/CC systems could become competitive with coal-based co-generation systems in Sweden. In fact, the relative value attributed by the markets to heat and electricity will influence the competitiveness of BIG/CC systems vis-à-vis coal-based co-generation systems because of the difference in power to heat ratios (about 1 for BIG/CC systems and about 0.4 for coal-based co-generation). In the case of electricity only generation, the short-term costs of electricity from BIG/CC fuelled with wood chips from SRC and forestry residues are likely to remain significantly higher compared to the costs of electricity from conventional coal and gas generation. However, the cost difference may be reduced if transmission losses and potential cost benefits of the decentralised nature of BIG/CC systems are taken into consideration. Transmission losses are likely to add €2 – 2.5/kWh to the cost of electricity from large conventional generation systems. Also, a preliminary analysis (Taylor, 1996) indicates that the benefits of embedded generation could range between €12 – 17/kWh, as a result of reduced costs associated with high voltage transmission infrastructure. If costs associated with losses and high voltage transmission infrastructure are added to the generating costs of conventional coal and natural gas plants, the gap between the cost of supplying electricity by BIG/CC and conventional systems is significantly reduced, making BIG/CC systems competitive in some cases.

3 Direct and indirect employment

Direct employment generated by the different activities and stages of the biomass fuel cycle has been estimated using a detailed fuel cycle activities inventory database and model (see Annex 1). The estimates are based on manpower required for biomass production, transport and conversion, as well as for ash disposal activities. Indirect employment has been estimated using the EMI input-output model (see Section 3.2 in Chapter 2) based on Swedish and UK input-output tables and on the average annual expenditure generated by the biomass and coal fuel cycles calculated in the spreadsheet model. Direct and indirect employment figures are shown in Table 31 and Table 32 as a function of useful energy output (heat and electricity in the case of the Värnamo plant and electricity only in the case of the ARBRE plant) and as a function of fuel cycle expenditure.

Table 31: Direct and indirect employment generated by the biomass and reference fuel cycles [man h/MWh]

	Värnamo		*Coal (S)*		ARBRE		*Coal (UK)*	
	Direct	Indirect	*Direct*	*Indirect*	Direct	Indirect	*Direct*	*Indirect*
Production	0.21	0.25	-	*§*	0.72	1.4	*1.2*	*0.38*
Conversion	0.67	0.84	*0.25*	*0.48*	0.99	1.5	*0.27*	*0.52*
Clean-up	§	§	*§*	*§*	§	§	*§*	*§*
Total	0.88	1.09	*0.25*	*0.48*	1.71	2.9	*1.47*	*0.90*

- indicates values are not considered because outside boundaries of the study
§ indicates values are not significant

Table 32: Direct and indirect employment generated by the biomass and reference fuel cycles [man h/M€]

	Värnamo		*Coal (S)*		ARBRE		*Coal (UK)*	
	Direct	Indirect	*Direct*	*Indirect*	Direct	Indirect	*Direct*	*Indirect*
Production	6700	8100	-	*§*	14000	20400	*37100*	*12400*
Conversion	22000	29300	*15200*	*27600*	19100	29500	*8500*	*15900*
Clean-up	§	§	*§*	*§*	§	§	*§*	*§*
Total	28700	37400	*15200*	*27600*	33100	49900	*45600*	*28300*

- indicates values are not considered because outside boundaries of the study

§ indicates values are not significant

Employment figures have to be interpreted with care because of the early development stage of the biomass energy systems considered. Improvements in the efficiency of the fuel cycle are likely to lead to lower specific direct labour requirements.

The most significant benefits in terms of employment would result in countries which rely on imported fossil fuels. Indirect employment generated by investments in sectors of the economy other than those directly involved in the biomass fuel cycle appears also to be significant, but may vary significantly according to the structure of the economy.

Biomass production is likely to be less labour intensive than coal production, but similar or slightly more labour intensive than natural gas production. Direct employment associated with natural gas production is estimated at approximately 0.22 man h/MWh of electricity generated by a CCGT plant. If compared roughly on a per unit energy content of biomass fuel input to the plant basis, the ARBRE plant results in a higher labour requirement associated with fuel production and transport compared to the Värnamo plant. This is due to a more labour intensive production of SRC fuel compared to forest fuel and longer average transport distances.

The biomass conversion stage appears significantly more labour intensive than the coal conversion stage. Most of this difference is likely to be due to the demonstration nature of the biomass conversion facilities. However, biomass conversion may be expected to remain a more labour intensive activity compared to coal conversion and more so compared to natural gas conversion.

Net employment, direct and indirect, generated by the Värnamo biomass fuel cycle compared to the reference coal fuel cycle can be derived from Table 31 and is estimated at 1.24 man h/MWh. This represents an annual net employment requirement of close to 82,000 man h compared to the reference coal fuel cycle, equivalent to about 43 full time jobs. The total number of jobs, direct and indirect, generated by the fuel cycle would be 68, of which about 30 would be directly associated with fuel cycle activities and be generated in the vicinity of the plant. It is important to note that employment associated with coal production is not accounted for as it occurs outside the national boundaries and that the labour requirement estimates for the biomass fuel cycle may be slightly high because of its early commercialisation stage.

Net employment, direct and indirect, generated by the ARBRE biomass fuel cycle compared to the coal reference fuel cycle can be derived from Table 31 and is 2.23 man h/MWh. For a plant like the ARBRE Plant this represents an additional employment requirement of 133,000 man h compared to the reference coal fuel cycle, corresponding to about 70 full time jobs. The total number jobs, direct and indirect, generated by the fuel cycle would be 143, of which about 53 would be directly associated with fuel cycle activities and be generated in the vicinity of the plant.

Comparing labour requirements based on expenditure, presents an additional difficulty due to the fact that the high expenditure characterising demonstration fuel cycles is likely to result in an underestimation of direct employment. However, the values in Table 32 provide an indication of specific employment generated per unit of expenditure and could be used as a basis for comparison with employment generated by other expenditure in the energy sector. The above general conclusions on the labour requirements of the fuel cycles remain valid.

Efficient biomass systems will aim at reducing labour requirements and overall little additional employment generation would result from biomass fuel cycles compared to conventional fuel cycles. The importance with regard to employment lies in the sectors and regions where biomass fuel cycles will generate employment. The creation of employment is a top priority in many regions and where biomass resources are available for energy use they could provide an important source of jobs.

4 Environmental analysis

The environmental analysis will focus on those impacts of the biomass fuel cycles judged to have potentially significant effects and designated as priority impacts. A quantification of the impacts is not always possible or meaningful due to lack of knowledge and uncertainties in the fuel cycle and in the impacts it may cause. Where the quantification of potential priority impacts is not possible, the impacts and precautions necessary to avoid or mitigate them have been discussed qualitatively. The quantitative analysis has focused on certain atmospheric emissions of the fuel cycle. These are the emissions from the fuel cycles which can be determined with greatest certainty and those for which dose-response relationships leading to the impacts are available, and, for the fuel cycles considered, are the ones which are likely to lead to the most significant impacts. Atmospheric emissions are likely to result in the most significant impacts in the case of 'good practice' biomass fuel cycles. They are also considered to result in the impacts of greatest importance in the case of the reference fossil fuel cycles (CEC, 1995 and 1998a). It is then important to compare the biomass and reference fuel cycles on this basis. This section will limit itself to the determination of the quantifiable emissions and to the qualitative discussion of the non-quantifiable impacts. The quantification of the impacts and the calculation and discussion of the externalities will be the subject of Chapter 8.

4.1 Atmospheric emissions analysis

This section determines and discusses the direct and indirect atmospheric emissions of the biomass and reference fuel cycles.

4.1.1 Direct fuel cycle emissions

Detailed fuel cycle inventory calculations (see Annex 1) are performed to provide estimates for the emissions occurring at each stage of the biomass fuel cycle (Table 33; Table 34; Figure 22; Figure 24). Distinction is made between non-stack emissions (i.e. emissions from the production and transport stages) and stack emissions (i.e. emissions from the conversion stage) for the total fuel cycle emissions (Figure 23; Figure 25). It is important to note that most direct emissions from the biomass fuel cycle are likely to occur within a 100 km x 100 km grid around the plant. The distinction between non-stack and stack emissions is of no relevance with regard to greenhouse gas emissions due to their global effect. An aggregate value for the total fuel cycle emissions is also calculated.

For the reference systems, aggregate emissions are provided for the extraction, transport and processing stages of the fuel cycles and separate emissions are provided for the emissions from the conversion stage (see Annex 1 and Section 7 of Chapter 4). The total fuel cycle emissions are also calculated. For the Swedish case study, where different fuel cycles contribute to the reference system (see Section 7 of Chapter 4), emissions have been attributed based on the energy contribution breakdown provided in Table 12 in Chapter 4.

All emissions in Table 33 and Table 34 correspond to direct emissions from fuel cycle activities. The different fuel cycles can then be discussed and compared on the basis of the emissions values provided.

Table 33: Emissions breakdown for the Swedish case study (all emissions in mg/kWh except CO_2 equivalent emissions which are in g/kWh)

	Production[1]	Transport	Conversion	Clean-up	Total
NO_x Varnamo min	46.45	13.37	62.33	0.25	122.39
NO_x Varnamo max	110.64	20.05	780.20	0.37	911.26
NO_x System1	47.44		217.66	0.77	265.87
NO_x System2	50.94		327.88	0.00	378.82
CO Varnamo min	18.70	3.98	190.03	0.07	212.79
CO Varnamo max	44.54	5.97	380.07	0.11	430.69
CO System1	2.98		184.46	0.23	187.66
CO System2	4.22		238.14	0.00	242.36
CO_2 (equ.) Varnamo min	4.24	3.19	0.29	0.02	7.74
CO_2 (equ.) Varnamo max	10.83	4.78	0.29	0.02	15.93
CO_2 (equ.) System1	62.08		369.95	0.01	432.04
CO_2 (equ.) System2	64.12		425.42	0.00	489.54
PM Varnamo min	7.00	1.12	6.08	0.02	14.22
PM Varnamo max	16.67	1.68	6.08	0.03	24.46
PM System1	8.39		7.38	0.06	15.83
PM System2	8.39		7.38	0.00	15.76
SO_2 Varnamo min	0.97	0.31	43.48	0.01	44.76
SO_2 Varnamo max	2.30	0.46	86.96	0.01	89.73
SO_2 System1	189.77		616.08	0.02	805.87
SO_2 System2	191.93		616.08	0.00	808.02
NMHC Varnamo min	8.57	0.46	0.00	0.01	9.03
NMHC Varnamo max	20.40	0.69	0.00	0.01	21.10
NMHC System1	1.89		0.00	0.03	1.92
NMHC System2	3.41		0.00	0.00	3.41

[1] includes production, transport and fuel processing for fossil fuel cycles (Gover et al., 1996)
System 1: Electricity and heat from CFB coal plant and additional electricity from hydropower
System 2: Electricity and heat from CFB coal plant and additional electricity from CCGT

Table 34: Emissions breakdown for the UK case study (all emissions in mg/kWh except CO_2 equivalent emissions which are in g/kWh)

	Production[1]	Transport	Conversion[2]	Clean-up	Total
NO_x ARBRE min	116.97	66.30	159.05	0.81	343.13
NO_x ARBRE max	380.69	79.63	398.02	0.97	859.31
NO_x Coal	26.56		2340.00	2.51	2369.07
NO_x Gas	24.98		787.30	0.00	812.29
CO ARBRE min	47.09	19.74	484.91	0.24	551.99
CO ARBRE max	153.27	23.71	969.83	0.29	1147.09
CO Coal	11.53		129.18	0.75	141.46
CO Gas	8.87		383.48	0.00	392.35
CO_2 (equ.) ARBRE min	27.50	15.81	0.74	0.19	44.25
CO_2 (equ.) ARBRE max	89.50	18.99	0.74	0.23	109.47
CO_2 (equ.) Coal	96.68		957.39	0.04	1054.11
CO_2 (equ.) Gas	14.59		396.22	0.00	410.80
PM ARBRE min	17.62	5.57	15.52	0.07	38.77
PM ARBRE max	57.35	6.69	15.52	0.08	79.64
PM Coal	32.50		180.00	0.21	212.71
PM Gas	0.00		0.00	0.00	0.00
SO_2 ARBRE min	2.43	1.52	12.38	0.02	16.34
SO_2 ARBRE max	7.91	1.82	37.13	0.02	46.88
SO_2 Coal	0.35		1068.35	0.06	1068.76
SO_2 Gas	15.45		0.00	0.00	15.45
NMHC ARBRE min	21.57	2.28	0.00	0.03	23.88
NMHC ARBRE max	70.21	2.74	0.00	0.03	72.97
NMHC Coal	7.34		18.00	0.09	25.42
NMHC Gas	10.85		10.96	0.00	21.80

[1] includes production, transport and fuel processing for fossil fuel cycles (Gover et al., 1996)

[2] emissions for the ARBRE plant are based on a 32% conversion efficiency, as opposed to a 40% efficiency which would be typical of a commercial system, which leads to emissions slightly higher than those expected for future systems

Atmospheric emissions from biomass fuel production are a result of farming and forestry machinery operation and may also result from the volatilisation of agrochemicals (e.g. nitrogen fertiliser is assumed to result in greenhouse gas emissions in the form of nitrous oxide (N_2O)). The biomass fuel production stage acts as a sink for carbon dioxide emissions, through the growth of plant matter and possibly increased soil carbon content. Because of the lack of data on soil carbon storage, this aspect has not been considered in the greenhouse balance calculations and it has been generally assumed that all carbon stored as a result of biomass fuel production is released in the conversion stage. Net carbon dioxide emissions will result from the biomass fuel cycle due to the use of fossil fuels to run machinery and equipment employed at various stages of the fuel cycle. Exhaust gases from trucks used in the transportation of biomass fuel and ash also contribute to the fuel cycle atmospheric emissions. Emissions resulting from the transport of sewage sludge have not been considered as part of the biomass fuel cycle since its transport, in particular to agricultural land, would occur anyway as part of the sewage treatment activities. Emissions from the conversion stage originate from the plant stack. Other emissions occur at the plant site but are considered to be small in comparison to those from the stack and have been neglected. Trace air pollutants such as dioxins and heavy metals are not considered to be of relevance for the biomass fuel cycles considered and are assumed not to be of significance for the reference fuel cycles (CEC, 1995 and 1998a).

Figure 22 and Figure 24 provide insight on the total biomass fuel cycle emissions, the contribution of the different stages of the fuel cycle and the comparison of emissions between the biomass and reference systems. Figure 23 and Figure 25 distinguish between stack and non-stack emissions for the different fuel cycles.

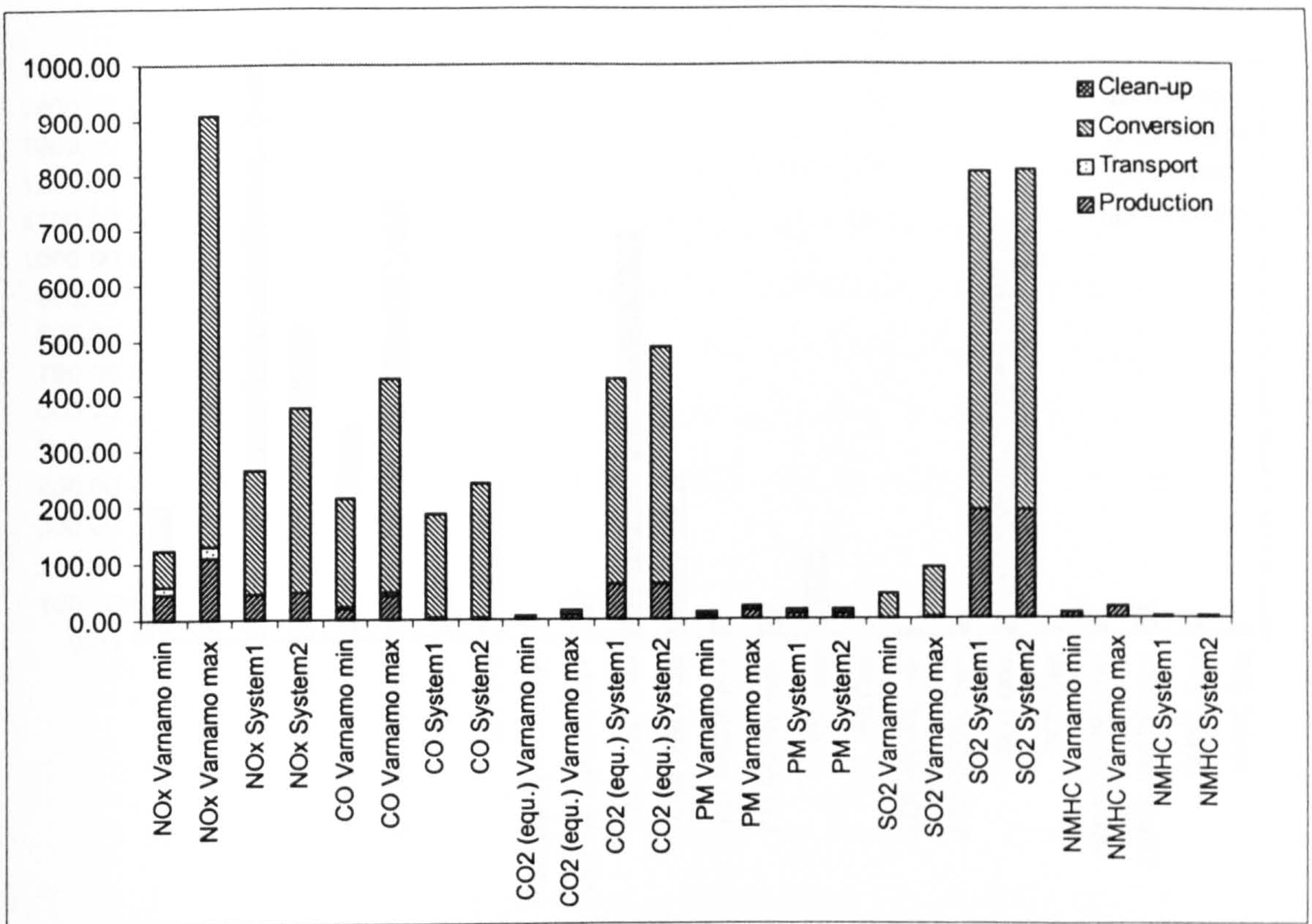

Figure 22: Emissions from the biomass and coal fuel cycles for the Swedish case studies (emissions are expressed in mg/kWh for all substances except CO_2 for which they are expressed in g/kWh)

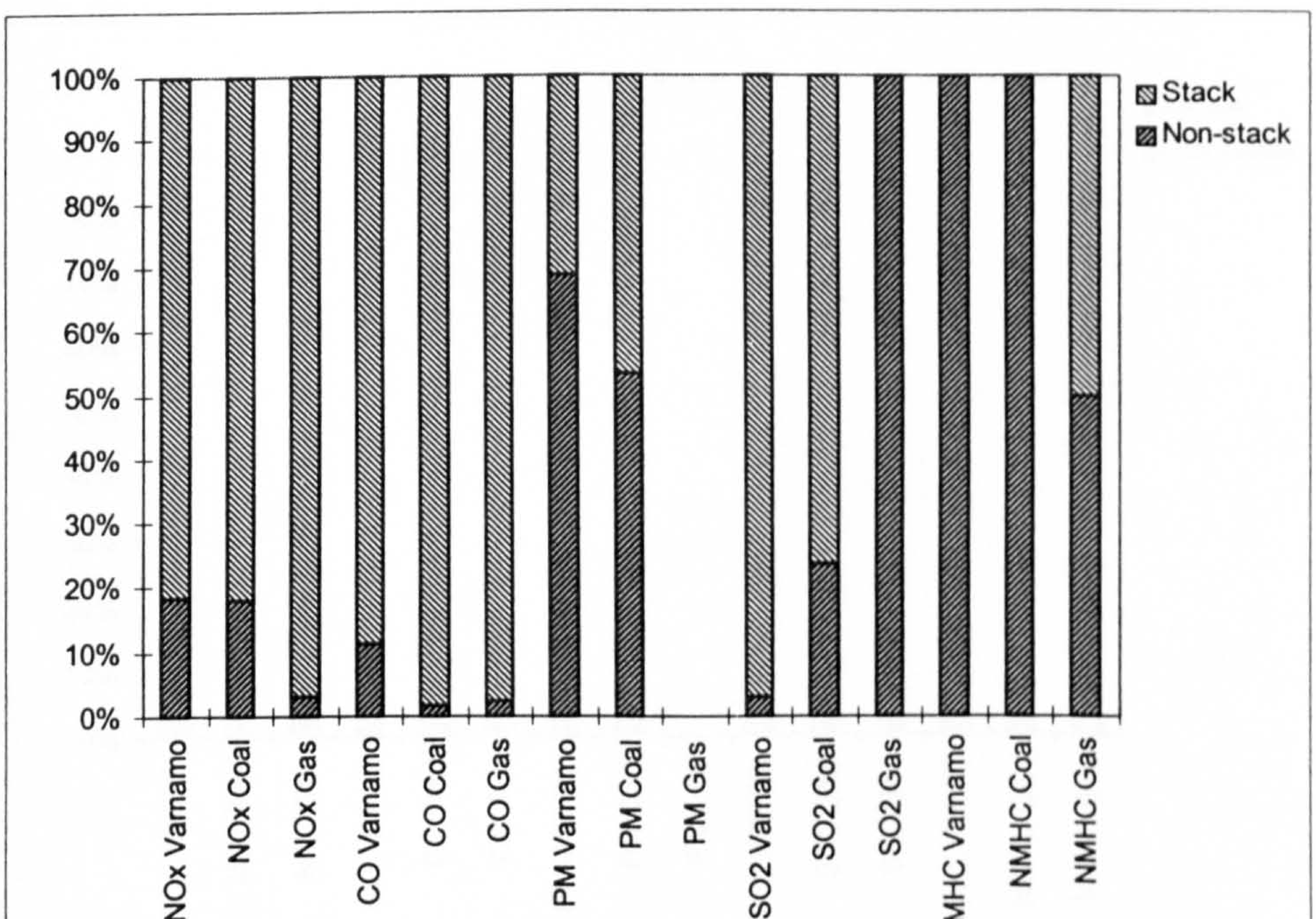

Figure 23: Emissions location for the biomass and coal fuel cycles for the Swedish case studies

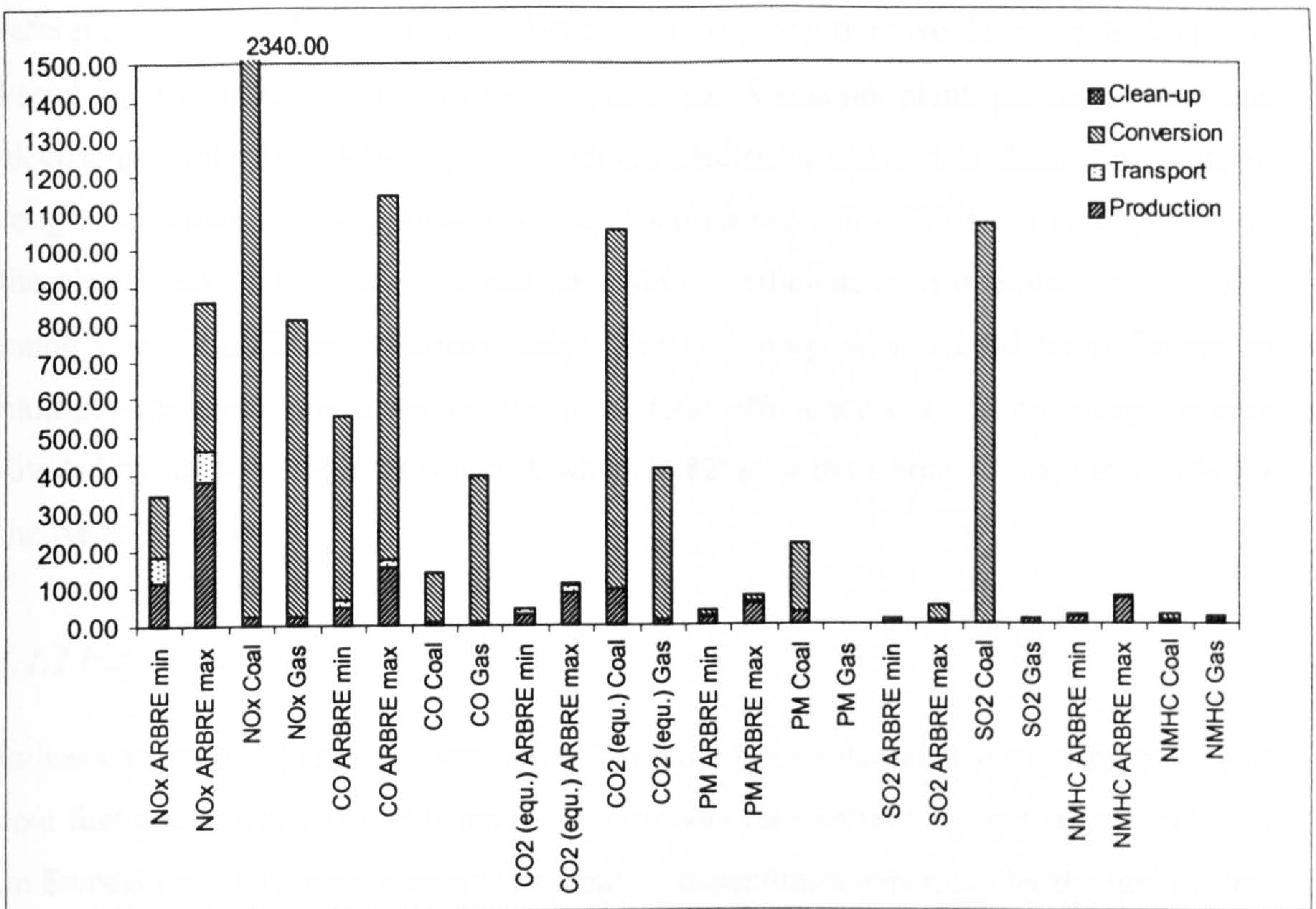

Figure 24: Emissions from the biomass and coal fuel cycles for the UK case studies (emissions are expressed in mg/kWh for all substances except CO_2 for which they are expressed in g/kWh)

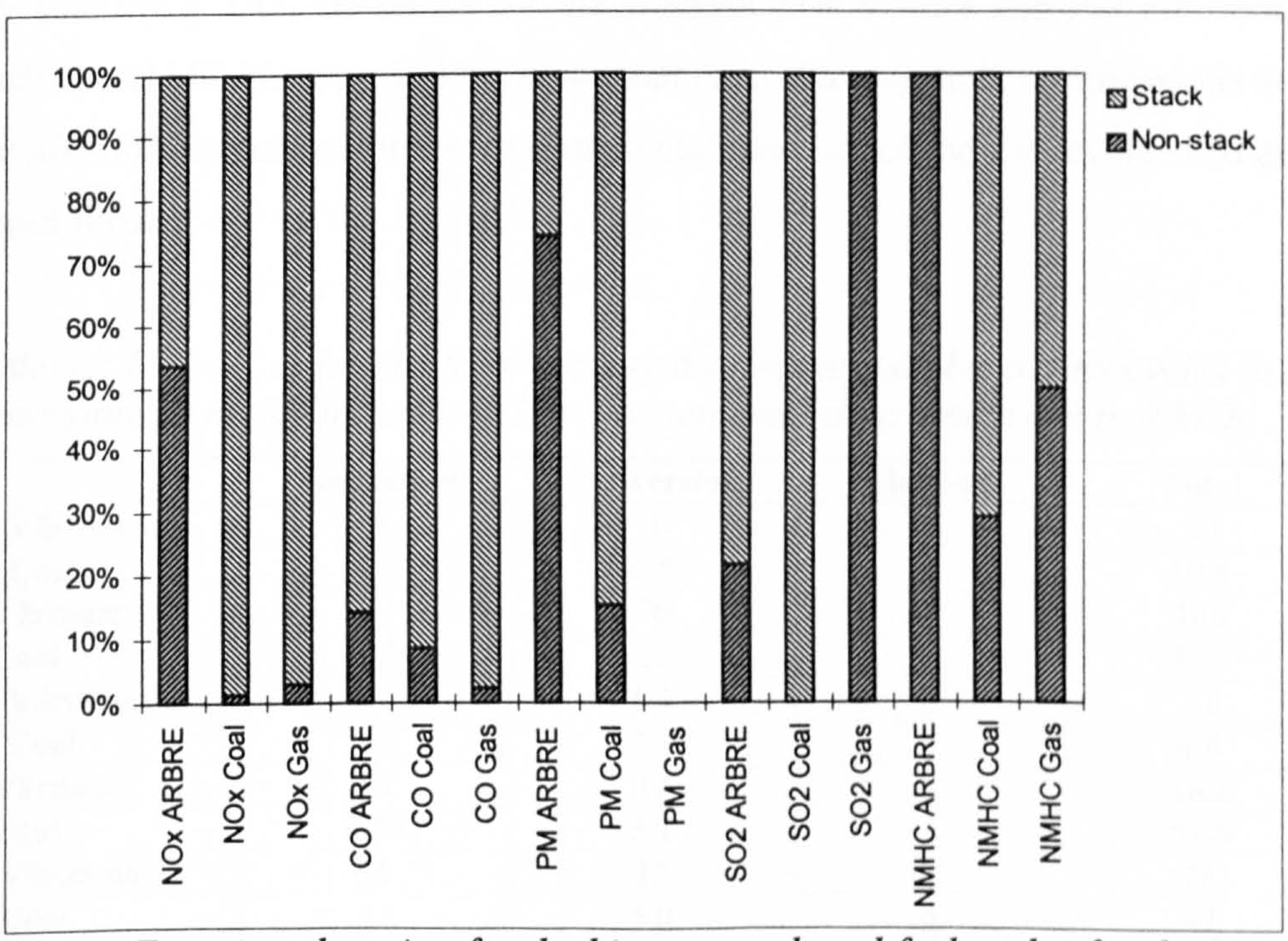

Figure 25: Emissions location for the biomass and coal fuel cycles for the UK case studies

The emissions in Table 33 and Table 34 are expressed per unit of useful energy output in the form of heat and electricity and allow to compare the biomass fuel cycles with the reference systems. However, it is difficult to compare the two biomass fuel cycles, based on the values in the tables, because the Värnamo plant produces heat and electricity while the ARBRE plant produces electricity only. It is though possible to roughly compare the two biomass fuel cycles on a per unit of biomass energy input to the plant basis, as both plants would have similar efficiencies if operating in the same mode (that is CHP or electricity only). For this purpose it would be sufficient to multiply the emissions given by the plant total efficiency (i.e. useful energy output divided by input fuel energy content), which is 82% for the Värnamo plant and 32% for the ARBRE plant.

4.1.2 Indirect emissions

Indirect emissions (Table 35 and Table 36) have been calculated for the biomass and coal fuel cycles using the EMI input-output model (see section 3.2 in Chapter 2) based on Swedish and UK input-output tables and on expenditure generated by the fuel cycles. They are found to be of little significance compared to direct emissions and are generally about an order of magnitude smaller compared to direct emissions. Indirect emissions are of the same order of magnitude as direct emissions only when the latter are very small (e.g. CO_2 emissions for the biomass case studies and PM emissions for the Swedish and UK biomass and Swedish coal case studies). Indirect emissions are not likely to affect the outcomes of the environmental analysis of the fuel cycles and are not considered further.

Table 35: Indirect emissions from the Swedish biomass and coal fuel cycles (all emissions in mg/kWh except CO_2 equivalent emissions which are in g/kWh)

	Production	Conversion	Clean-up	Total
NOx Värnamo	14	16	§	30
NOx Coal	4.3	6.5	§	10.8
CO Värnamo	27	76	§	103
CO Coal	1.7	29	§	30.7
CO2 Värnamo	2.7	5.1	§	7.8
CO2 Coal	2.3	2.1	§	4.4
PM Värnamo	4.2	12	§	16.2
PM Coal	0.58	5.1	§	5.68
SO2 Värnamo	16	12	§	28
SO2 Coal	42	5.0	§	47
NMHC Värnamo	8.6	5.3	§	13.9
NMHC Coal	18	2.2	§	20.2

§ indicates emissions are not significant

Table 36: Indirect emissions from the UK biomass and coal fuel cycles (all emissions in mg/kWh except CO_2 equivalent emissions which are in g/kWh)

	Production	Conversion	Clean-up	Total
NOx ARBRE	94	53	§	147
NOx Coal	43	29	§	72
CO ARBRE	250	390	§	640
CO Coal	110	100	§	210
CO2 ARBRE	32	20	§	52
CO2 Coal	37	12	§	49
PM ARBRE	100	69	§	169
PM Coal	48	23	§	71
SO2 ARBRE	80	51	§	131
SO2 Coal	210	49	§	259
NMHC ARBRE	48	23	§	71
NMHC Coal	120	28	§	148

§ indicates emissions are not significant

4.1.3 Comparison of biomass and reference systems emissions

NO_x emissions in the case of the Swedish biomass fuel cycle range between about half and twice those of the reference systems. This result stresses the possible significance of NO_x emissions from the production and conversion stages of the biomass fuel cycle and consequently the attention that must be paid to such emissions. The low value for NO_x emissions from the biomass conversion stage is associated uniquely with the thermal NO_x component, which depends on the combustion temperature and the combustion characteristics of the gas turbine. Thermal NO_x emissions are equipment dependent and are specified by the gas turbine manufacturer. In this case the emissions associated with biomass conversion are about a factor four lower than those associated with coal combustion. A significant contribution to the total fuel cycle emissions comes then from the production stage, causing total emissions to be about a factor two lower than those of the reference system with the lowest emissions.

The high NO_x emissions value for the biomass conversion stage in the case of the Värnamo plant relates to the maximum NO_x emissions which could result from the sum of thermal and fuel NO_x. Fuel NO_x would result from the conversion of ammonia (NH_3) present in the fuel gas, if this were not removed by the gas clean-up system (i.e. hot gas filters). The high emissions value assumes that 60% of the nitrogen in the fuel is converted to ammonia in the gasifier (no catalytic reduction) and that all of the ammonia is converted to NO_x in the gas turbine. In such case, the emissions from the conversion stage are three times higher for the biomass plant compared to the coal plant and about double those of the system including CCGT electricity, and the influence of the emissions from the production stage is less significant. Such high emissions are unlikely as catalysts would be used (e.g. in the bed material) to break down ammonia prior to its combustion, thus reducing NO_x emissions associated with fuel bound nitrogen.

If no fuel NO_x were considered, emissions from the Värnamo biomass conversion stage are estimated to be between about a factor four and a factor two lower than those of the coal conversion stage. The total biomass fuel cycle emissions would amount to between one third and two thirds those of the reference systems. The elimination of fuel NO_x emissions is imperative, otherwise the total biomass fuel cycle emissions would be two to three times higher than those of the reference systems.

For the UK biomass case study, based on low pressure gasification, no fuel bound NO_x component is present because all the ammonia is assumed to be washed out by the wet gas scrubbing equipment. The emissions from the ARBRE plant are considerably lower than those of the UK pulverised coal plant considered, between six and fifteen times lower. For the entire fuel cycle, the total emissions of the biomass fuel cycle are reduced to between three and seven times those of the coal fuel cycle because of the significant contribution of biomass production and transport activities.

CO emissions are similar for both biomass fuel cycles when compared on a per unit of biomass energy input to the plant basis, and they are assumed to be the same for both biomass conversion plants. From the data available, it appears that the CO emissions from the biomass fuel cycle are likely to be higher compared to those from the reference systems. The range of CO emissions for the biomass conversion facilities are based on measures carried out by Bioflow Ltd and estimates of turbine manufacturers (GEC Alsthom).

It is assumed that no net carbon dioxide emissions result from the biomass conversion stage, and the small contribution to carbon dioxide equivalent emissions from the conversion stage results from the small quantities of N_2O assumed to be emitted by the plant. Fuel cycle carbon emissions are then mainly a result of biomass fuel production and transport activities, and to a less extent of ash disposal activities. Although the emissions are low for both biomass fuel cycles, they are higher in the case of the ARBRE plant because of the more energy intensive activities associated with SRC as opposed to collection of forest residues. Biomass fuel cycles show very significant savings in greenhouse gas emissions compared to the reference systems considered. Greenhouse gas emissions can be reduced by about a factor thirty or more by the Swedish biomass fuel cycle compared to the reference systems based on coal co-generation and electricity from renewables or gas. The UK biomass fuel cycle can reduce emissions by a factor four or greater compared to CCGT electricity and by a factor ten or greater compared to coal electricity. The results not only emphasise the advantages of using biomass fuels, but also the advantages of co-generation.

Particulate emissions are similar for both biomass fuel cycles. They are assumed to be the same for both plants on a per unit of biomass energy input basis, and are derived from data measured by Bioflow Ltd at the Värnamo plant. It is assumed that the hot gas filter and wet gas scrubber remove particulates from the product gas with similar efficiency. Particulate emissions are similar for biomass and reference systems in the Swedish case. They are considerably lower for biomass compared to coal in the UK case (by about a factor three or more), but higher compared to electricity from gas (particulate emissions from CCGT based fuel cycles are considered to be nil).

SO_2 emissions for the biomass fuel cycles are between one and two orders of magnitude lower compared to the coal fuel cycles. Although very low for both biomass fuel cycles, the SO_2 emissions from the ARBRE plant per unit of biomass fuel energy input are lower than those from the Värnamo plant because of the high sulphur removal efficiency associated with the wet gas scrubbing system. SO_2 emissions are derived from an assumed range for the sulphur content of the biomass fuel (wood chips) based on its elemental composition. In the case of the HP-BIG/CC plant it is assumed that all the sulphur is converted to SO_2. For the LP-BIG/CC plant only 10% of the sulphur is assumed to reach the gas turbine, where it is converted to SO_2, because of the remainder being washed out in the wet gas scrubber. The use of certain bed materials (e.g. limestone) may further reduce SO_2 emissions.

Non-methane hydrocarbon emissions (NMHC) emissions are likely to be low in all cases and of the same order of magnitude for biomass and the reference systems considered.

Overall, biomass fuel cycles are likely to present significant advantages in terms of emissions compared to the reference systems considered, in particular with regard to SO_2, PM and CO_2 emissions. Significant advantages could also result for NO_x emissions if biomass fuel bound NO_x emissions are avoided. Most biomass and fossil fuel cycle emissions are from the stack. However, in the case of biomass fuel cycles important NO_x and PM emissions result from the machinery used in the production and transport stages of the fuel cycle. Possible reductions in NO_x and CO emissions should be considered for the biomass conversion facilities. Also, ways of reducing NO_x, CO and PM emissions from the biomass production and transport stages should receive attention.

4.2 Soil quality

There has been very little effort in the UK to investigate or map the risks of soil erosion. The only known map available refers to soil erosion by water under winter cereal cropping (SSLRC, 1993). This simply divides the country into areas of 'negligible' risk, 'moderate' risk or 'high risk'. No indication of rates of soil erosion is given, and wind erosion is not considered. The entire study region is defined as under negligible risk, except two small areas. These are at Eggborough itself (the study site) and Thorpe Willoughby 5 km to the north, where there is moderate risk. However, both of these sites are in areas where SRC is unlikely to be grown due to controls on nitrate applications under the Nitrate Sensitive Areas scheme, though it is generally thought that soil erosion rates under SRC will be lower than under other crops. For the UK case study, it appears that soil erosion is not a priority issue and thus any benefit is unlikely to be significant. This is not always the case in other areas of the UK where SRC may be grown in the future, and consideration should be given to the valuation of potential benefits of SRC over alternative land uses.

Soil erosion is not considered to be an issue in the case of the Swedish biomass case study. However, forest fuel extraction may impact on the soil's water, nutrient and acidification levels. The organic component of the soil is fundamental because of its water and nutrient retention ability. The extraction of felling residues from the forest may then affect the water and nutrient cycle. However, increased emissions of nitrogen to the atmosphere have caused greater deposition of nitrogen on forested areas, increasing their productivity and consequently the deposition of organic material. The prevention of forest fires has also contributed to an increase in deposited organic material. Since felling residues represent only a small part of the total supply of organic material from the forest, their partial removal is not likely to have detrimental consequences on the organic component of soils (Vattenfall, 1995).

Many natural forests around the world are deficient in nutrients such as nitrogen and phosphorus and to a lesser extent potassium, magnesium and sulphur. However, this is not the case for nitrogen and sulphur in regions characterised by acid deposition. Felling residues result in more ammonium being mineralised from the soil organic material. The ammonium can then lead to the formation of nitrate, which is then easily leached. The process is an acidifying one and may result in nutrient loss (i.e. leaching of calcium, potassium and manganese) and release of toxic substances (i.e. dissolution of aluminium in water). The greatest risk of nitrogen leaching occurs during the clear-cut phase. Although nitrogen is an essential nutrient, when present in excess it may cause changes in the flora and fauna, increase the risk of nutrient imbalance, give rise to nitrate and to nitrogen leaching to waterways. Excessive nitrogen may also result in microbial formation of N_2O which contributes to global warming and to stratospheric ozone depletion.

When forestry waste is left to decompose sulphur will be released as sulphide during the mineralisation process. Hydrogen sulphide can then be oxidised by microbes to sulphate. This is also an acidifying process. The extent of the acidification contribution of decomposition will depend on the amount of mineralisation of the organically bound sulphur. When the forest waste is burnt, a fraction of it is emitted as sulphur dioxide and the remaining part is found in the ashes as sulphate and residues from the gas cleaning process. The sulphur dioxide emitted eventually ends up on the soil as sulphuric acid. Therefore, in both cases sulphur will have an acidifying contribution.

Forest fuel contains about 10 times more nitrogen than sulphur and thus changes in the nitrogen cycle will bear greater consequences on acidification. In cases where soil acidification is a problem because of high deposition of sulphur and nitrogen, the removal of forest residues will reduce nitrogen input and thus reduce soil acidification. Only a small part of the nitrogen and sulphur in the biomass will then be returned to the soil via acidic deposition from atmospheric emissions from the conversion stage. It is also important to bear in mind that about 70% of a tree's nutrients are concentrated in the foliage, twigs and fine roots, which are generally not collected as fuel. Critical levels of nitrogen acidic deposition in Southern Sweden range between 3.5 and 7 kg N/ha/yr. Current annual deposition exceeds the critical level and is estimated at 7 to 10.5 kg N/ha/yr. Residues of tree harvesting activities are estimated to leave about 150 - 200 kg of organically bound nitrogen per hectare in the field. The partial removal of the residues will clearly reduce the acidification potential compared to a situation where residues from forestry activities are left in the field. Careful evaluation of the removal of felling residues and of the return of ashes is essential in order to avoid nutrient depletion in certain areas (ashes return minerals but not nitrogen). A proper management of felling residues and ashes is then important for maintaining nutrient balance, mitigating acidification and reducing the risk of leaching of harmful substances.

4.3 Water use and quality

Water use and quality impacts are mainly likely to be associated with the biomass production stage. For the small-scale demonstration plants considered, no significant releases to water should occur at the conversion stage. However, the liquid effluent from the wet gas scrubbing equipment used in the ARBRE plant needs attention as it may contain nitrogen compounds, tars and other organic compounds. Significant impacts are unlikely when using adequate water treatment and management technologies. In the case of larger plants, the use of flue gas condensing equipment may lead to an additional liquid effluent which may require treatment.

Water use and quality impacts may be of significance in the case of SRC plantations. Hall et al. (1996) have carried out a recent major study of the hydrological impact of SRC. Water use and quality measurements related to poplar and willow coppice trials were made at several sites over 3 years in the UK, and a water use model developed. The use of sewage sludge as a fertiliser was also investigated. A key conclusion is that in dry areas of the UK the high water use of SRC could have a serious impact on groundwater recharge and spring/stream flow. The impact of water pollutants, principally nitrates, would be exacerbated by the lower dilution rate. However, this impact is not considered to be as worrying as the impacts of high water use itself.

4.3.1 Water Use

It was found that annual transpiration from SRC after 3 years of establishment exceeds all other ground covers with the exception of coniferous forest, and significant soil moisture deficits develop before a reduction in transpiration is seen. Further evaporative loss is caused by the high rate of rainfall interception.

In drier parts of the UK (the Southeast, and some areas such as the Yorkshire case study area) the effective precipitation is below 150 mm. This is the difference between the rainfall and evaporation from grass growing on a soil of medium water availability, and represents the water available to maintain stream flow and aquifer recharge. The conclusion of the analysis is that 'large scale plantation of SRC in the driest parts of the country will result in the annual net recharge to aquifers and drainage to rivers and streams being reduced by up to 80 mm where a grassland catchment is wholly converted to SRC'. The amount of water added during each sewage sludge application is likely to be of the order of 10 - 20 mm. This would go some way to offsetting the high evaporation losses from SRC.

The impact of these high evaporation rates is that springs and streams could dry up sooner and for longer, and recharge to aquifers could be reduced. The economic damages could be measured in terms of higher costs for potable water supply (exacerbated by the concentration of pollutants caused by low dilution rates). The reduction in stream flow could also affect the recreation value of rivers. The scale of the ARBRE project is not likely to cause any significant adverse effect related to water use. However, the above considerations indicate that water use needs to be carefully addressed when considering more extensive SRC schemes.

4.3.2 Water quality

Where effective precipitation is low, even quite small rates of nitrate leaching can lead to high concentrations of nitrate in drainage water. It should be noted that high water demand by SRC would reduce the effective rainfall, so the concentration of nitrates in drainage water could be greater than in a reference case where equivalent sewage sludge or fertilisers are added to grass or arable crops.

Atmospheric inputs of nitrogen are expected to be almost sufficient for growth of SRC, making the use of artificial fertilisers less necessary (Hall et al., 1996). Without artificial fertilisation the average nitrate concentrations in drainage water were found to be very low, and comparable to unfertilised grassland. Thus where SRC is established on set-aside land and is managed without addition of fertilisers there should be no net impact in terms of nitrate pollution. Hall et al. (1996) also found that 'at the 3 sites studied where sewage sludge was applied average nitrate concentrations were significantly higher in the topsoil (13 - 90 mg/l NO_3-N) and some of this increase was apparent below 1 m, indicating that some increase in nitrate leaching to surface and groundwater was likely'. The authors felt unable to offer a dose-response relationship between the rate of sewage sludge application and the amount of nitrate leaching, due to insufficient monitoring to date. However, in areas of low effective precipitation (less than 150 mm/yr) 'even low rates of nitrate leaching could give rise to nitrate concentrations close to or exceeding the 11.3 mg/l NO_3-N limit for drinking water'.

It is difficult to assess how sewage sludge application will affect water quality in the region around the ARBRE plant. Groundwater in the area is contaminated by sulphates and nitrates, and has high concentrations of iron and manganese. The site overlies a highly permeable aquifer and the soils have a low attenuation potential. This means that any pollutants will rapidly reach the aquifer and disperse. Although SRC is not to be extensively planted in the case of the ARBRE project, precautions need to be taken concerning the rate and location (e.g. NVZs) of sewage sludge application. Significant damages due to nitrate pollution of groundwater are unlikely because of the legislation encouraging farmers not to grow SRC in areas of nitrate sensitivity. Furthermore, the source of nitrate pollution, sewage sludge, would anyway be applied to agricultural land in the area in the reference case, and thus the fuel cycle will not result in any additional pollution. Indeed there could be some net benefit, given the high rate at which willows take up nitrogen, however, it would have to be weighed against the possibly lower effective precipitation.

4.4 Application of Sewage Sludge

The application of sewage sludge to SRC serves as a sludge disposal route and as a provision of nutrients and water for plant growth.

The UK undertook to end disposal of sewage sludge at sea as of the end of 1998. There is then pressure to find alternative disposal routes and land application is considerably cheaper than incineration. About 50% of sewage sludge produced in the UK was disposed of to agricultural land in the early 1990s (MAFF, 1992), and the quantity is on the rise. Its application is regulated by the EC Directive 86/278/EC, implemented in the UK by the Sludge (Use in Agriculture) Regulations of 1989, and by the EC Nitrate Directive 91/676/EC. The main regulatory requirements relate to limits on the existing heavy metal content of the soil to which the sludge is to be applied, particularly lead, cadmium, mercury, copper, zinc and nickel, and on the rate of heavy metals and nitrogen application. Regulation also applies to prohibition of animals grazing and harvesting of foods eaten raw for a period after application.

Trials of sewage sludge application to willow SRC plantations on less fertile soils suggest a yield increase of 16 - 26%, compared to non-fertilised trials (Riddell-Black et al., 1996a).

Contamination by heavy metals present in the sewage sludge is a concern, in particular in acidic soils where most metals become more available and can reduce soil micro-fauna, restrict crop growth and be toxic to humans and animals. Indeed the limits set by UK legislation on the use of sludge vary with the pH of the soil, but values adopted in the UK remain high compared to those of other European countries (e.g. Denmark). Soils chosen for application of sludge in the UK have, on average, slightly lower background concentrations of metals than the national average soils (MAFF, 1993). The Foggathorpe 2 Association soils present in the region around the ARBRE plant are prone to acidity and particular care would have to be exercised when considering application of sewage sludge to these soils. Cadmium, zinc and copper are the metals of greatest concern. However, over the last decade the concentrations of these metals in sludge applied to land have fallen considerably, due to the tightening of rules on discharges.

There is some evidence that willow selectively takes up heavy metals, and trials have shown cadmium concentrations in willow SRC to be 5 times that of the soil, at 2.5 mg/kg (dry matter) (Riddell-Black et al, 1996b). Major anthropogenic sources of cadmium are the burning of fossil fuels, phosphorous containing fertilisers and sewage sludge. Atmospheric deposition of cadmium in the UK averages 3 g/ha/yr, and phosphate fertilisers contribute about 4 - 5 g/ha/yr. Yorkshire water will be applying 7 odt/ha of sewage sludge (as a slurry of approximately 4% solids) every 3 years. This could represent an input of cadmium of

7.5 g/ha/yr or 3.5 g/ha/yr, based on median and low UK cadmium concentrations in sludge from MAFF (1993), respectively. The latter value should be a more appropriate estimate since the ARBRE project should utilise sludge from less polluted sources. As a comparison, the permissible maximum annual addition of cadmium in the UK is 150 g/ha/yr (MAFF, 1992). The burning of willow SRC will concentrated the cadmium in the ash produced at the gasification facility. If the ash is disposed to landfill, and therefore removed from the system, a net environmental benefit may occur compared to its disposal on agricultural land, where greater amounts of cadmium would tend to accumulate in the soil. If cadmium concentrations pose no concern, if they can be concentrated in a small fly ash fraction which is then disposed to landfill, or if the ash can be treated for their removal (Obernberger et al., 1997), then it may be desirable to return ash to the land as a source of nutrients.

Zinc, readily translocated to the leaves of plants, restricts photosynthesis and affects the metabolism of elements such as iron resulting in a yellowing of the whole plant. These effects are seen long before there is any health risk to animals or humans. Zinc could be added to land by the ARBRE project at a rate of approximately 2.1 kg/ha/yr or 1.1 kg/ha/yr, based on median and low UK cadmium concentrations in sludge from MAFF (1993), respectively. The latter value should be a more appropriate estimate since the ARBRE project should utilise sludge from less polluted sources. As a comparison, the permissible maximum annual addition in the UK is 15 kg/ha/yr (MAFF, 1992).

Copper is not easily taken up by plants, and is more of a risk in terms of poisoning to ruminants.

The application of sewage sludge can lead to an excess presence of nutrients, which can cause eutrophication in water courses if excessive run-off takes place, and to other problems associated with the presence of nitrate in water. In Nitrate Vulnerable Zones a limit of 210 kg N/ha/yr will be enforced by December 1999, and this will be reduced to 170 kg N/ha/yr by December 2003 (MAFF, 1993 and 1994). This, rather than heavy metals content, is likely to become the limiting factor on sewage sludge application.

4.5 Biodiversity

There is very little data and little agreement on the biodiversity benefits or damages caused by short rotation coppice. In the UK, recent work appears to indicate that biodiversity is likely to benefit from the introduction of SRC (ETSU, 1999) and the Royal Society for the Protection of Birds is cautiously positive. Two Red List and three Amber List bird species make regular use of SRC, and a further five Red List and three Amber List species make occasional use of it. For example, willow seems to favour the presence of songbird species such as the migrant warbler (Sage and Robertson, 1994)

The UK Good Practice Guidelines on Short Rotation Coppice for Energy Production (ETSU, 1996) suggests ways in which SRC can be managed to enhance biodiversity benefits. The birds expected to benefit from the crop itself are skylarks, pipits, wagtails, migrant warblers, reed buntings, thrushes, tits, finches, some songbirds and snipe. SRC could also increase bird numbers in nearby woodland, as it would provide a food source in the form of insects. Use of wide headlands and rides is encouraged as it provides habitat for wild flowers and weeds, butterflies, beetles and some parasitic species that could help reduce pest outbreaks. Approximately 10% of the land area should not be planted. Some loss of yield (possibly less than 10% given the benefits of edge effects and healthier crops) must be taken into account.

Insect biodiversity is certain to benefit from SRC compared to most other land uses. However, economic valuation of this benefit is even less feasible than for large attractive species such as birds. Soil micro-fauna are also expected to benefit. However, in the case of the ARBRE project the application of sewage sludge (and possibly wood ash) and some build up of heavy metals in the upper soil which it may cause, could adversely affect soil biota.

SRC is likely to present biodiversity advantages over arable crops, but advantages become less discernible when comparing SRC to other land uses, including land left fallow (both could be managed to promote biodiversity). Conceptual difficulties in monetary valuation of biodiversity, compounded by the lack of clear evidence on the actual benefits or disbenefits from SRC, make it difficult to provide any estimate of possible externalities.

Biodiversity is also an issue in managed forests. Felling operations, resulting in the biomass residue used for energy, are likely to be the most disruptive to biodiversity, but practices involved in the collection of residues are also of importance with regard to biodiversity. In the past forest management has often paid little attention to nature conservation, leading to a decrease in the number of plant and animal species present. However, improved management practices can foster the biodiversity of managed forests and ecologically sound practices are increasingly being adopted. In Sweden, good practice measures are observed in forestry and residues collection activities to foster biodiversity. Management practices vary according to land characteristics and individual management plans are now available to forestry owners. Biodiversity is fostered by practices such as leaving healthy and rotting trees and residues in the fields, preserving wet areas and minimising soil disturbance during forestry activities.

4.6 Amenity

Rural areas can no longer be considered exclusively as areas set aside for food or other crop production. They are now also a recreational resource for many people, valued for their tranquillity, clean air, visual appeal and sporting opportunities. Conserving the peace and promoting the enjoyment of the countryside by the public have been factors in determining agricultural policy in the UK since 1986 (Agriculture Act, 1986). Similarly, forests are highly valued for their recreational aspects (Jörgensen et al., 1998).

When considering rural amenity attention must focus on two distinct groups of people: those living and working in the area concerned, and those visiting for recreational purposes or commuting to urban areas to work. People living and working in a rural area where a biomass energy industry emerges are likely to welcome the new jobs and economic vitality it brings, and thus the impacts related to noise, odours or visual intrusion will be lessened. In contrast, those visiting or living in rural areas specifically because of the rural amenity value are more likely to express resistance to changes in their environment.

Sadler (1993) surveyed public perception of SRC in the UK. SRC was found to be potentially acceptable to most users of the countryside, but concern was voiced that rapid, large-scale expansion of SRC would cause considerable loss of rural amenity value. These fears focus on 'over-regimented' and 'industrial' landscapes, noise, impacts on wildlife, and increased traffic on rural roads. The features of rural amenity on which a biomass industry may have an impact are: landscape/visual, noise, odours, access and biodiversity.

4.6.1 Landscape

SRC grows to over 3 metres in height prior to harvest, and with the introduction of higher yielding clones this may be a low estimate. Because the trees are deciduous and fast-growing, a landscape containing SRC will change in colour and structure over the seasons. Much has been written on how plantations can be planned to mitigate the visual impact of SRC, and this advice is formalised in biomass industry guidelines (ETSU, 1996 and ARBRE, 1996b).

An objective valuation of landscape changes involving SRC is difficult, but existing research suggests that it may be negatively valued. In Biewinga and van der Bijl's (1996) study of the sustainability of energy crops in Europe, poplar and willow SRC score negatively in their LCA system because the plantations would reduce the 'openness' of the landscape. This was considered to be the case in all 4 of the locations examined, despite the fact that structure and colour changes in the landscape are perceived positively.

A possible negative valuation of landscape changes associated with SRC in the UK may find support in the work of Willis and Garrod (1992). They used WTP surveys to assess people's preferences for different landscape types in the Yorkshire Dales National Park. This is a farmed landscape, but one which is exceptionally attractive. The overwhelming preference was for today's landscape, amongst visitors and residents alike, and semi-intensive and intensive agricultural landscapes were universally unpopular. Semi-intensive and intensive agricultural landscapes were valued at zero, while the average WTP for today's landscape was £22/yr (about €27) for residents and £26/yr (about €31) for visitors.

The implications of this study are not conclusive with respect to the development of biomass for energy land uses. The WTP figures are higher than one would expect to find in a typical agricultural setting because of the beauty of the area studied and the number of outside visitors who visit specifically for appreciation of the landscape. However, it does suggest the following considerations regarding valuation of landscape changes:

- Agricultural intensification is seen to be detrimental to landscape value;
- In areas of high landscape value, the aggregate WTP of visitors (regarding landscapes) can exceed that of residents;
- Any change from the status quo in the appearance of landscapes is likely to be unpopular, unless it involves greater provision of existing features which are greatly appreciated such as stone walls, wild flowers and broad-leaved woodlands.

In the area where the ARBRE plant is situated the landscape is rather monotonous, with large fields of arable crops broken up by power stations and roads. Therefore one would not expect SRC to be detrimental to the landscape, and might even be positively valued for adding colour and structural variety.

Some consideration should be given to the visual impact of storing harvested stems on agricultural land. The ARBRE project plans to store bundles of harvested stems at the edges of fields. These may be more visually intrusive than the crop itself, as piles of bundles about 3 m high, 5 m wide and 15 m long are expected for each hectare of SRC. The presence of several of these piles in a single field for up to a year could be quite visually striking.

Arriving at an economic valuation of the landscape impacts of biomass for energy is difficult. However, it is important to be aware of the strong feelings people can have about changes to landscapes, and for developers to be sensitive to this issue. Undoubtedly, people's perceptions of changes are influenced by an understanding of the reasons for such changes, and therefore public education concerning the benefits of energy crops should be considered before their introduction.

4.6.2 Noise

Noise nuisance is related to the level of background noise, people's expectations, time of year (in summer people spend more time outdoors and with windows open) and on subjective associations with the source (Lines et al., 1993). In rural areas background noise levels are generally low, and people expect more tranquillity than in urban areas, so consideration should be given to possible nuisance caused by activities associated with biomass production for energy. Lines et al. (1993) carried out a UK based survey of rural people's experience of annoying noise in the countryside, and examined the complaints received by local authorities relating to rural noise. They found that agriculture was not a major source of noise nuisance. Road traffic, domestic activity and aircraft were the most significant sources.

Noise levels from biomass collection and chipping activities could be a cause of nuisance, but the activities generally occur far from dwellings. Noise exposure is mostly of concern for the workers. Recommended exposure levels are below 75 dB(A) and collecting and chipping equipment may generate noise levels above 100 dB(A). The use of equipment for the protection from noise (e.g. sound proof cabins) is recommended. In the case of the ARBRE plant, harvested stems will be stored in their fields of origin, and then chipped when needed at the power plant. Per hectare of SRC, every 3 years some 3 hours will be needed to chip the stems, and 4 trucks needed to transport the chips to the facility (ARBRE, 1996a). This could cause some annoyance, particularly in the summer months.

Noise from biomass fuel transport appears not to be a significant source of nuisance in Sweden. If suitably organised, transport should not represent a source of noise nuisance in the UK either.

Recommended noise levels in Sweden for inhabited areas range between 40 and 55 dB(A) and wood chip storage terminals may produce noise levels of about 50-55 dB(A) at 500 m. Significant noise levels may also result from other pre-treatment and conversion equipment at the plant site, but attenuating measures can be taken. The avoidance of noise nuisance to residential areas is an important consideration in the siting of the plant.

4.6.3 Odours

Lines et al. (1993) found that odours in the countryside were a relatively minor source of annoyance, comparable to noise as a cause for complaints.

Biomass energy projects may cause some nuisance due to odours. Odours from wood chip drying have been a source of annoyance at the Värnamo plant in Sweden, and the president of the commune reported that this was the only cause of public complaint relating to the power station that they had received (Egerhag, 1998). A flue gas condensation system has been installed to reduce vapour emissions from the drying facility, and complaints have ceased.

Where sewage sludge is applied to agricultural land an unpleasant odour may persist for about a week. However, land disposal is the likely disposal route whether SRC is grown or not. If people mistakenly associate the SRC with the cause of the odour, this would adversely affect the public perception of the crop.

5 Energy analysis

Direct and indirect energy requirements have been estimated for the Värnamo and ARBRE fuel cycles. Direct energy requirements consist of fossil fuel input for machinery operation and the energy required for the construction of the conversion plant. The only indirect energy requirement considered to be significant consists of energy embodied in the machinery employed. The energy embodied in agrochemical inputs is generally a significant contributor to the indirect energy requirements of biomass fuel cycles. However, the biomass fuel cycles considered are characterised by very low agrochemical input levels, with no significant effect on the energy balance.

A detailed energy analysis has been performed based on the fuel cycles inventory database and model (see Annex 1) and the principal outcomes for the facilities considered are shown in Table 37. The energy ratio is expressed relative to the thermal energy content of the biomass fuel and also relative to the useful energy (electricity and/or heat) output to account for system efficiencies.

Table 37: Energy analysis summary for biomass fuel cycles (annual basis)

Facility	Electric / heat output (net)	Biofuel input	Total non-renewable energy input	Specific non-renewable energy requirement		Energy ratio*	
	TJ	TJ	TJ	MJ/MJ_b	MJ/MJ_{out}	$(MJ/MJ_b)^{-1}$	$(MJ/MJ_{out})^{-1}$
Värnamo	92 (el.) 143 (heat)	287	19	0.067	0.081	15	13
ARBRE	214	670	37	0.055	0.14	20	8

MJ/MJ_b: specific non-renewable energy input per unit of biomass energy input
MJ/MJ_{out}: specific non-renewable energy input per unit of useful energy (heat and electricity) output
* the energy ratio is the inverse of the specific non-renewable energy requirement

As a comparison, Table 38 summarises the outcomes of an approximate energy analysis for the reference coal and gas fuel cycles.

Table 38: Energy analysis summary for the fossil fuel reference fuel cycles

Facility	Specific non-renewable energy requirement		Energy ratio*	
	MJ/MJ_{fuel}	MJ/MJ_{out}	$(MJ/MJ_{fuel})^{-1}$	$(MJ/MJ_{out})^{-1}$
Coal - Sweden	1.13	1.24	0.89	0.81
Coal - UK	1.11	3.27	0.90	0.31
Gas - UK	1.08	2.34	0.92	0.43

MJ/MJ_{fuel}: specific non-renewable energy input per unit of fossil fuel energy input
MJ/MJ_{out}: specific non-renewable energy input per unit of useful energy (heat and electricity) output
* see footnote in Table 14

Mortimer (1991) provides an energy ratio of about 11 for large hydroelectric schemes. The outcome of the energy analysis is very favourable for both the Värnamo and the ARBRE fuel cycles. A comparison of the specific non-renewable energy requirements shows that about 15 to 23 times less non-renewable energy in the form of fossil fuel is required by the biomass fuel cycles to produce the same energy output (heat and electricity) as the fossil fuel cycles. In particular, the Swedish biomass fuel cycle requires between 13 and 17 times less non-renewable energy compared to the reference systems, and the UK biomass fuel cycle requires about 23 times less non-renewable energy compared to the reference system. It is important to note that the biomass systems considered have low electrical efficiency (about 32%) due to the demonstration nature of the plants. Higher energy ratios relative to plant output could then be achieved by the biomass plants (note: the energy ratio associated with a particular efficiency can be obtained by multiplying the energy ratio relative to biomass energy input by the conversion efficiency).

6 Conclusion

The single most important barrier to the market penetration of biomass energy remains its higher cost relative to fossil fuels. Biomass fuels delivered to the plant are more expensive than fossil fuels, therefore it is imperative to both reduce biomass fuel cost and use efficient conversion systems. Sensitivity analysis indicates that a 10-20% reduction in biomass fuel costs appears reasonable in the short-term. In particular, higher yields, reduced machinery costs and shorter transport distances can significantly affect biomass fuel costs. Also, BIG/CC systems present significant efficiency gains over other biomass conversion systems for electricity generation. Biomass conversion costs associated with BIG/CC demonstration plants are high. However, costs could be significantly reduced for higher capacities and by learning-by-doing. The gradual introduction of larger biomass systems (e.g. capacities between 30 and 60 MW_e) would lead to a convergence of energy costs towards those of energy from conventional sources, in particular for co-generation applications. The favourable consideration of economic benefits which could result from the decentralised nature of biomass plants could contribute significantly to its economic competitiveness.

Employment generation is often hailed as a potential benefit of renewable energy vis-à-vis conventional generation. However, it does not appear as if the biomass fuel cycles considered will present significant advantage in terms of employment generation, except if biomass production displaces the import of fossil fuels, in which case a significant net employment benefit would occur at the national level. With regard to employment, the benefit lies rather in the preservation and creation of jobs in rural areas through economic diversification.

Biomass fuel cycles present great benefits in terms of resource use leading to significant savings in non-renewable energy use compared to conventional fossil fuel cycles. Also, biomass fuel cycles result in significant reductions in direct emissions compared to reference fuel cycles, in particular coal. Greatest reductions result for SO_2, PM and CO_2 emissions. Significant reductions can also be achieved for NO_x if fuel bound emissions can be avoided. Ways of reducing NO_x, CO and PM emissions, in particular from the biomass production and transport activities, deserve attention.

Biomass procurement should not have significant impacts on soil quality. In the case of SRC, soil quality may improve because of the nitrogen stabilisation properties of SRC, foliage deposition and reduced erosion compared to alternative land uses, in particular arable crops. In the case of forestry residues, their removal is unlikely to have negative impacts on soil nutrients, in particular if these are returned to the forest through ash recycling. In fact, the removal of nitrogen tends to reduce nitrate leaching and acidification leading to nutrient loss and the release of toxic substances.

Water use and quality issues deserve particular attention in the case of SRC, in particular for future larger biomass schemes. In dry areas SRC could affect groundwater recharge and stream flow. Furthermore, the impact of pollutants, nitrates in particular, could be exacerbated by lower dilution rates. Attention must then be paid to the siting of SRC in relation to nitrogen sensitive areas, especially where sewage sludge is to be applied to the fields. If suitable siting and good practice is followed, the application of sewage sludge to SRC can present benefits compared to its application to other crops because of the significant nitrogen uptake and nitrogen stabilisation properties of SRC.

The main concern with regard to sewage sludge application is nitrogen leaching, mentioned above, and heavy metals contamination. However, if good practice and monitoring is followed significant impacts are unlikely. In fact, the application of sewage sludge to SRC could again result in benefits compared to its application to other crops because of SRC's uptake of heavy metals such as cadmium. Attention needs to be paid to possible accumulation of heavy metals in ash. The limiting factor in the application of sewage sludge is likely to nitrogen rather than heavy metals.

The effect of biomass production on biodiversity is difficult to estimate. There is growing evidence that SRC provides a favourable habitat for a number of animal and plant species, and that it may present benefits compared to more intensive agriculture and even fallow land. In the case of forestry, felling is the activity most disruptive to biodiversity, the collection of residues being of relatively minor significance. Suitable management practices to foster biodiversity is fundamental for both SRC and forestry activities. The effect of sewage sludge application on biodiversity requires greater consideration.

Consideration of amenity issues such as landscape, noise and odours might seem rather trivial compared to matters such as employment, climate change or air pollution. The development of biomass energy systems may have beneficial environmental and social effects, and therefore one could argue that we should minimise the nuisances it could cause, but not be too concerned by them. This could be a great mistake.

Measured in terms of willingness to pay reactions to noise, smells and landscape change could be significant. Objections could also be expressed in campaigns and co-ordinated efforts to block planning applications for biomass energy developments, akin to the reactions to wind power in the UK. Therefore, amenity issues should not be neglected, however trivial or difficult to value in monetary terms they appear.

Biomass power is generally perceived to be 'green' (where people are aware of it at all), but the same applies to wind power and yet this has provoked considerable opposition in the UK for aesthetic reasons.

CHAPTER 6

Gasification of Sugarcane Residues in Brazil

1 Introduction

There is a large untapped biomass potential in Brazil. The use of biomass for power generation, in particular via modern conversion technologies such as circulating fluidised bed combustion and steam turbine (CFB/ST) systems and biomass integrated gasification and gas turbine combined cycle (BIG/CC) systems, could contribute significantly to satisfying future power needs (Larson et al., 1989; Walter, 1994 and Bauen et al., 1998b). Modern biomass conversion technologies emit low levels of pollutants and biomass could provide an indigenous renewable fuel with little or no CO_2 emissions. The use of biomass in the pulp & paper, agro-industry (including sugar and alcohol industry) and steel industry already contributes significantly to reduced CO_2 emissions. A more efficient use of the biomass fuel, in particular in association with co-generation aiming at the sale of surplus electricity to the transmission grid, could result in additional benefits associated with displaced generation. The use of alcohol in transport, as an unblended fuel or blended with petrol and eventually with diesel, serves to mitigate air pollution and greenhouse gas emissions from transport.

The scope of this chapter is to provide a detailed description of gasification-based biomass fuel cycles fuelled with sugarcane residues in Brazil. It begins with an introduction on the use of sugarcane residues for energy and an estimation of the energy potential from sugarcane residues in Brazil. This is followed by a discussion on the surplus electricity potential at sugarcane processing plants based on their characteristics. A discussion on the framework for biomass energy exploitation in Brazil follows, including an overview of the energy sector, its evolution and the key players likely to be involved in the biomass energy schemes, which is of interest in the assessment of the potential for implementation of the systems considered. Regional environmental and socio-economic information provides the background for the economic and environmental analysis of the biomass fuel cycles. A detailed description of the fuel cycle leading to gasification-based co-generation at the sugarcane processing plant provides a technical discussion, analysing the strengths and weaknesses of the fuel cycles, and provides the basis for the analysis, including the identification of the fuel cycles' priority impacts. Finally, reference systems are defined, which will serve as a basis for comparison to assess the economic and environmental performance of the biomass fuel cycles.

2 Sugarcane residues for energy

Bagasse resulting from the processing of sugarcane is widely exploited in the Brazilian sugar and alcohol industry to satisfy its mechanical and electrical energy, as well as process steam requirements. However, in Brazil, as in the majority of sugarcane producing countries, bagasse is generally converted to mechanical and electrical power with low efficiency due to the large quantities of bagasse available and to the need for its disposal. Much scope exists for an enhanced valorisation of this residue.

The harvesting of unburned sugarcane results in additional residues, consisting of dry and green leaves and tops, which we will refer to as harvest residues (also commonly referred to as barbojo or trash in the literature). Their quantity per tonne of cane is roughly equal to that of bagasse. Currently, most of these residues go up in smoke or are deposited in the fields as ash due to the widespread burning of the plantations in order to ease manual, and in some cases mechanical, harvesting. Recent legislation in the Brazilian state of São Paulo has decreed the suspension of pre-harvest burning by 2005 in areas suited for mechanical harvesting (estimated to be about 50% of the planted area) and by 2012 in the remaining areas (Braunbeck et al., 1999). An inexorable move towards the mechanisation of the harvesting process driven by regulation and economic efficiency (mechanical harvesting is likely to be more cost effective than manual harvesting) will lead to large quantities of harvest residues which can be potentially exploited for energy use. Braunbeck et al. (1999) provide a discussion on the present and future of sugarcane harvesting in Brazil.

The residues can be removed from the stalk in the field, at appropriate centralised cleaning centres or at the mill site. Experience gained so far in Brazil with the harvesting of unburned sugarcane does not allow to assert which harvesting and harvest residues recovery method is likely to be the most economically viable. However, there are some advantages associated with harvesting methods which leave the residues in the field for later collection. For example, storage as bales in the field avoids additional storage space at the mill, reduces transport volume, allows transport of residues to the mill when required which eases transport requirements during the milling season.

If the residues are removed from the cane stalk in the field, which is the case considered in the present study, part of these could then be collected from the field and used as a fuel, if their use proves to be economically and environmentally viable. Little experience exists worldwide on harvest residues collection activities, with sparse field tests having been carried out in the Dominican Republic, the Philippines, Puerto Rico, Jamaica, Hawaii and Thailand (see for example Winrock, 1991). In Brazil, interest in harvest residues is recent and research and field tests are currently being carried out by COPERSUCAR, a large co-operative of sugarcane and sugar and alcohol producers in the state of São Paulo, and by the Usina Santa Elisa in the state of São Paulo. COPERSUCAR is currently involved in a World Bank - Global Environment Facility part funded project on the use of sugarcane bagasse and harvest residues for electricity generation (CENBIO, 1998a).

Bagasse and harvest residues, the latter similar to bagasse in composition, can provide a valuable fuel for electricity generation via gasification, in particular gasification-based electricity generation (Walter, 1994; Williams and Larson, 1993). Biomass gasification coupled with single cycle advanced gas turbines or combined cycle gas and steam turbines (BIG/CC)) can achieve high generating efficiencies. However, little experience exists on the gasification of bagasse and harvest residues, with few tests having been carried out worldwide, mainly with bagasse. Tests with bagasse and harvest residues have been carried out for small-scale applications (e.g. in open top gasifiers in India) (Jorapur and Rajvanshi, 1995). For larger scale systems (e.g. circulating fluidised bed gasifiers), which are of interest to this study, limited laboratory scale tests have been carried out.

According to Walter (1994), gasification-based combined cycle systems are likely to be the most economically viable co-generation option in the case of an average sized Brazilian sugarcane processing plant (about 300 tonnes of cane stalk (tc)/h processing capacity). However, the technology is currently at the demonstration stage (see Chapter 3) and a series of technical difficulties are likely to have to be overcome (e.g. with regard to fuel processing and feeding to the gasifier, gasifier operating conditions and fuel gas cleaning) before the technology can be successfully demonstrated. Most of these issues are currently being addressed by research institutes and industry through laboratory, pilot and demonstration projects around the world.

Recent renewed interest in power exports from the sugar and alcohol industry is a result of technological advances and cost reductions of generating equipment, the likely greater availability of residues in the form of harvest residues, the ongoing reform of the electricity sector, increasing electricity demand, the financial crisis of the electricity supply sector which could result in the failure to meet demand, and the opportunity for the sugar and alcohol industry to diversify and enhance its competitiveness by generating additional revenues. Also, decentralised generation presents a number of additional benefits such as a more efficient energy supply, in particular in the case of co-generation, reduced costs, opportunities for local economic development, reduced environmental impacts and a diversification of the electricity supply system.

The Brazilian case study focuses on co-generation, on the electricity surplus potential in particular, in the sugar and alcohol industry using bagasse and harvest residues as a fuel. Combined gas turbine and steam turbine cycles integrated with atmospheric and pressurised circulating fluidised bed gasifiers (see Figure 7 and Figure *8* of Chapter 4) are considered because of their high fuel throughputs, flexibility with regard to fuel characteristics, high efficiencies and low emissions. First, the potential for electricity surplus based on sugarcane residues availability is assessed. Then, the private costs, energy balance and emissions to the environment of the fuel cycle are estimated, as these factors are likely to influence, although to different extents, an enhanced uptake of co-generation in the sugar and alcohol industry and the choice of equipment used. Economic, resource use and environmental aspects are discussed in relation to reference conventional power generation options (Chapter 7).

The energy potential, economic and environmental analysis is carried out for the sugarcane industry in general. The analysis considers a milling capacity range between 50 and 1050 tc/h typical of the Brazilian situation, a process steam requirement of 350 kg/tc, and average electrical and mechanical power requirements of 12.4 kWh_e/tc and 15 kWh_e/tc, respectively. The level of process steam requirement indicated is estimated to be attainable in Brazilian mills, which generally comprise back-end sugar refineries and annexed alcohol distilleries, with simple and low cost process modifications (Ogden et al., 1990; Zarpelon, 1997). Table 39 and Table 40 show the average operating characteristics of Brazilian mills and the characteristics of two particular mills, the average sized Usina Ester and the large Usina Vale do Rosario.

Table 39: Average operating characteristics of Brazilian mills

Process steam demand	504.3kg/tc
Mechanical power demand	15kWh/tc
Electrical power demand	12.4kWh/tc
Steam generator operating pressure	1.99MPa
Process steam pressure	247kPa

Table 40: Characteristics of the Usina Ester and Usina Vale do Rosario

Name	Usina Ester	Usina Vale do Rosario
Milling capacity (tc/h)	380	1,040
Milling season (days)	180	180
Extraction process	Milling	Milling/diffusion
Process steam (kg/tc)	450	425
Mechanical power (kWh/tc)	12.6	10.6
Electrical power (kWh/tc)	11.8	13.9

3 Energy potential from sugarcane residues in Brazil

The Brazilian sugarcane harvest of 1996/97 produced about 273 Mt of cane stalk for a sugar and alcohol production of about 13.5 Mt and 13.7 Mm^3, respectively (Macedo, 1998). The sugarcane industry in Brazil is concentrated in the state of São Paulo which contributes about 60% of the harvested cane, about 50% of the sugar production and about 70% of the alcohol production. Harvested cane stalk yields are also highest in the state of São Paulo where they are about 80 t/ha/yr. Production of sugar and alcohol takes place in autonomous sugar and alcohol plants or in annexed sugar and alcohol plants. Most alcohol produced is destined for transport use either as unblended fuel (hydrous alcohol) or as a petrol additive (anhydrous alcohol). The trend in sugarcane production shows an annual increase in production of about 2%.

Based on the 1996/97 sugarcane harvest of about 273 Mt of cane stalk for Brazil and on the assumption that 0.316 odt of sugarcane waste arise per tonne of cane stalk[11] (Macedo, 1998), the total amount of sugarcane waste, consisting of similar amounts of bagasse and cane residues, is estimated at about 86 Modt. While we can assume that all

[11] A tonne of cane stalk will hereafter be referred to as tc.

the bagasse is recoverable, by no means all the cane residues will be recoverable. If we make a conservative estimate that only 50% of the fields are suitable for mechanical harvesting systems, based on present technology, and that only 50% of the waste from these fields is recoverable because of agronomic reasons and losses at various stages of the process (most likely, up to 70% of the harvest residues could be recovered from the fields), then about 11 Modt of cane residues from the fields could be used for energy or other purposes. The total recoverable residues (bagasse and cane residues) would then be 54 Modt (Table 41).

A 25% harvest residue recovery will constitute the base case for the present study. No definite values exist at present on the harvest residues recovery potential and the percentages provided give an indication which is likely to vary according to regional topography and to the availability of more precise agronomic data. The harvest residues recovery estimate presented here is considered conservative.

Table 41: Sugarcane waste quantities and energy content (1996/97 harvest basis)

Cane stalks	273 Mt
Sugarcane waste quantities	
Bagasse	43 Modt
Harvest residues	43 Modt
Harvest residues (25% recovery)	11 Modt
Sugarcane waste energy content	
Bagasse	817 PJ
Harvest residues	817 PJ
Harvest residues (25% recovery)	209 PJ

The calorific value of bagasse and harvest residues is estimated at 19 GJ/odt, leading to a maximum thermal energy content of the residues recoverable from the 1996/97 harvest of about 1,026 PJ[12], of which 817 PJ are associated with bagasse and 209 PJ are associated with harvest residues. Assuming a 30% electric conversion efficiency, about 85 TWh of electricity could be produced per year, which represents about 32% of the total 1995 electricity consumption for Brazil. An average electricity capacity of about 10 GW_e could be associated with sugarcane residues, which represents about 17% of the national installed electricity capacity. There is, therefore, great scope for enhanced exploitation of the energy content of sugarcane residues and for surplus electricity production within the sugar and alcohol industry. The potential for surplus electricity from co-generation depends on biomass availability, mechanical and electrical power

[12] 1PJ = 0.278TWh

requirements of the plant, process steam requirements of the plant and efficiency of the co-generation system. The exploitation of the potential will depend on technical, economic, regulatory and policy aspects, as well as on the availability, costs and environmental effects of competing power sources.

4 Processing plant characteristics and surplus electricity potential

Walter (1994) provides the average operating characteristics for existing mills in Brazil shown in Table 39. A steam production rate of 1,754 kg/MWh$_e$ has been estimated for a combined gas and steam turbine cycle operating in co-generation mode, which assumes that steam is expanded in a steam turbine to a pressure of 2 bar (Larson and Williams, 1990; Consonni and Larson, 1996; Larson, 1994). Based on performance calculations performed by Consonni and Larson (1996) and Larson (1994), net electric efficiencies for LP-BIG/GTCC and HP-BIG/GTCC systems are estimated to be 42% and 45%, respectively, in electric power only mode, and 36% and 39%, respectively, in co-generation mode. For the purpose of the calculations in the present study, we have chosen a LP-BIG/GTCC system for which tests with sugarcane residues are planned (CENBIO, 1998a).

Based on the process steam requirement of the mill and on the steam production rate of the co-generation system, it is possible to estimate the required installed generating capacity at the mill. Figure 26 shows the required installed co-generation capacity, based on the above steam production rate, as a function of mill capacity and process steam demands (250 kg/tc, 350 kg/tc, and 450 kg/tc).

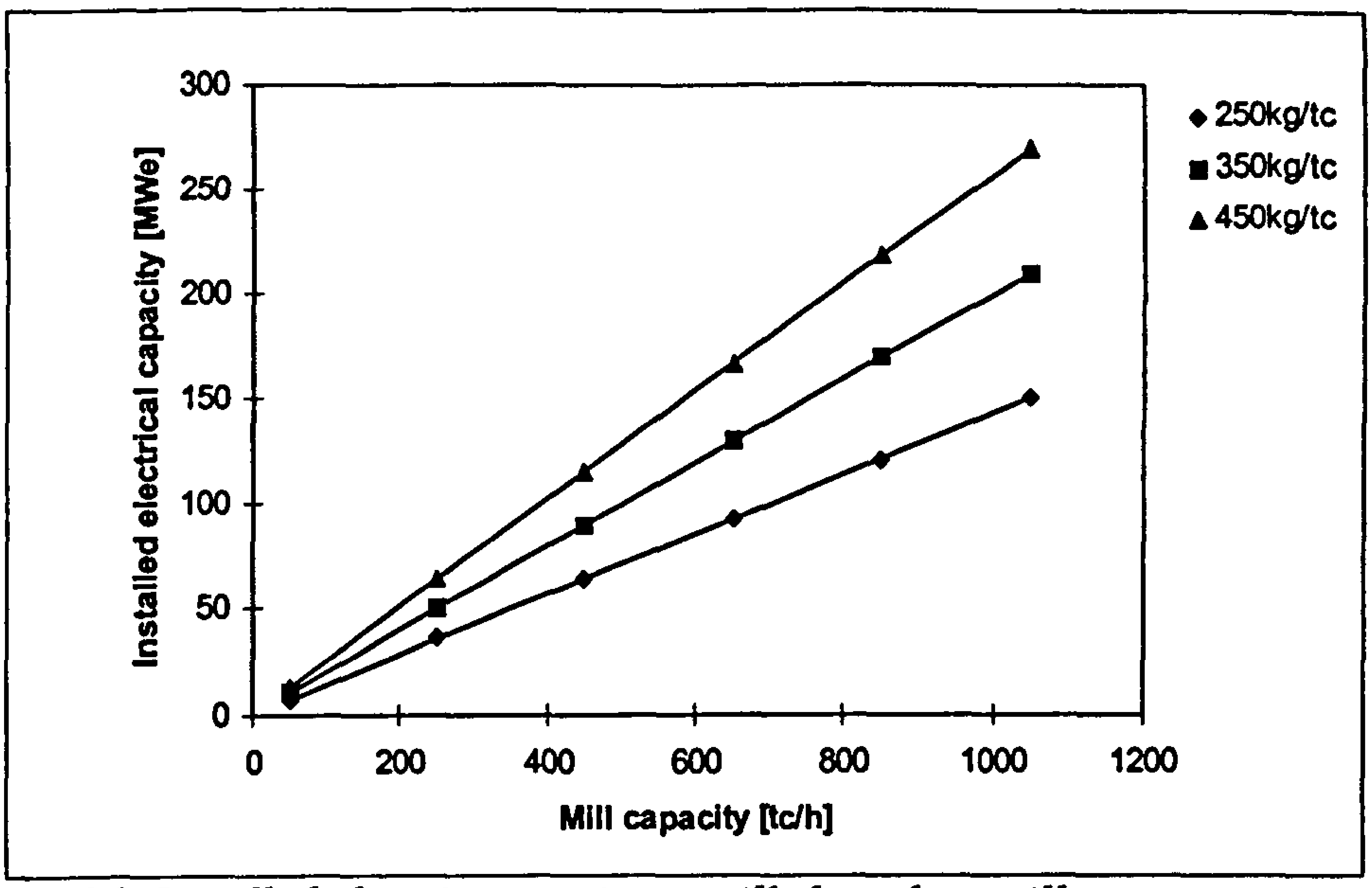

Figure 26: Installed electric capacity at mills based on mill steam requirement

The residues requirement as a function of the mill capacity and process steam demand is calculated based on the required installed capacity and is compared to residues availability (Figure 27 and Figure 28).

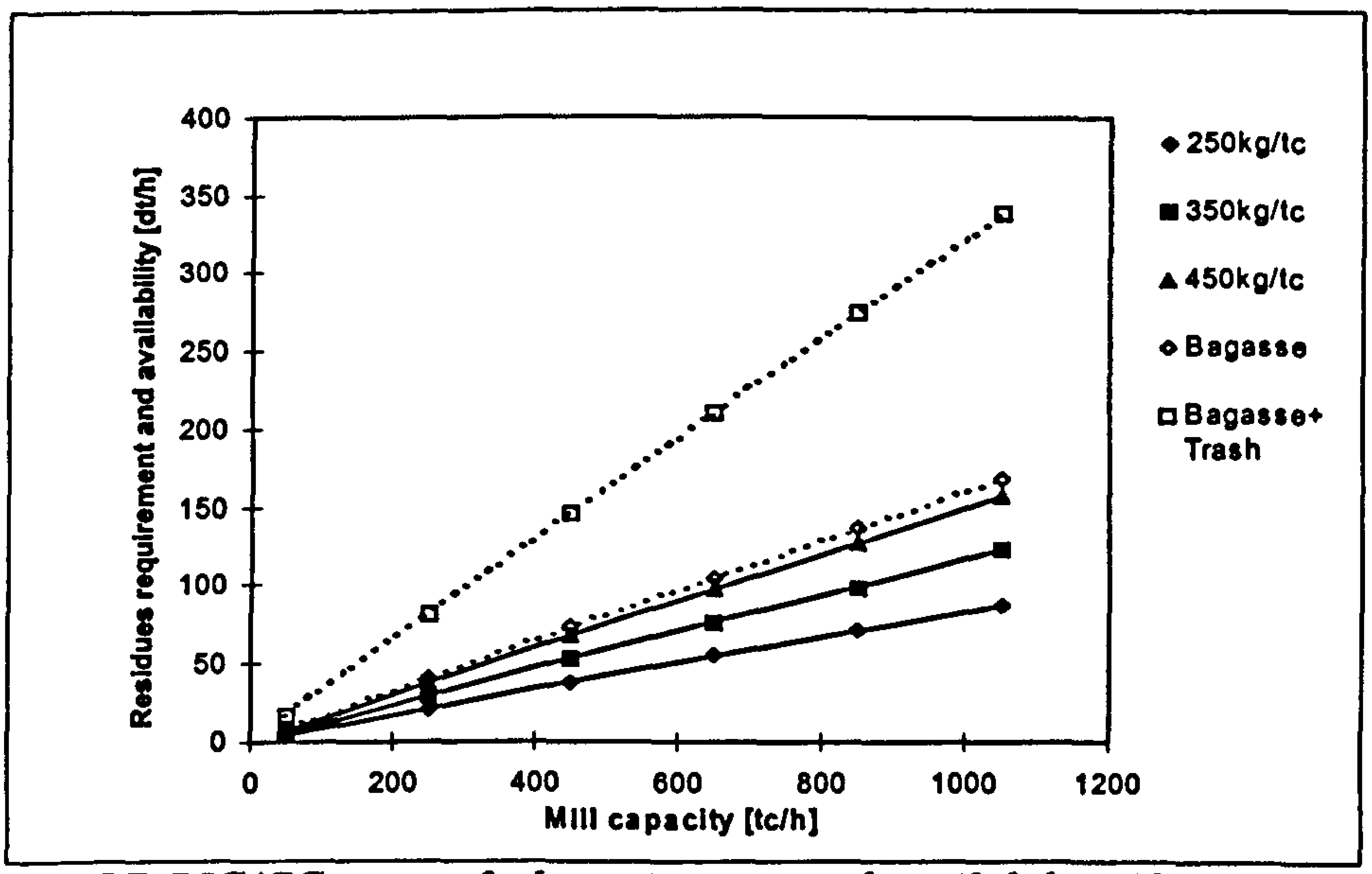

Figure 27: LP-BIG/CC system fuel requirement and availability. Note: Trash means harvest residues

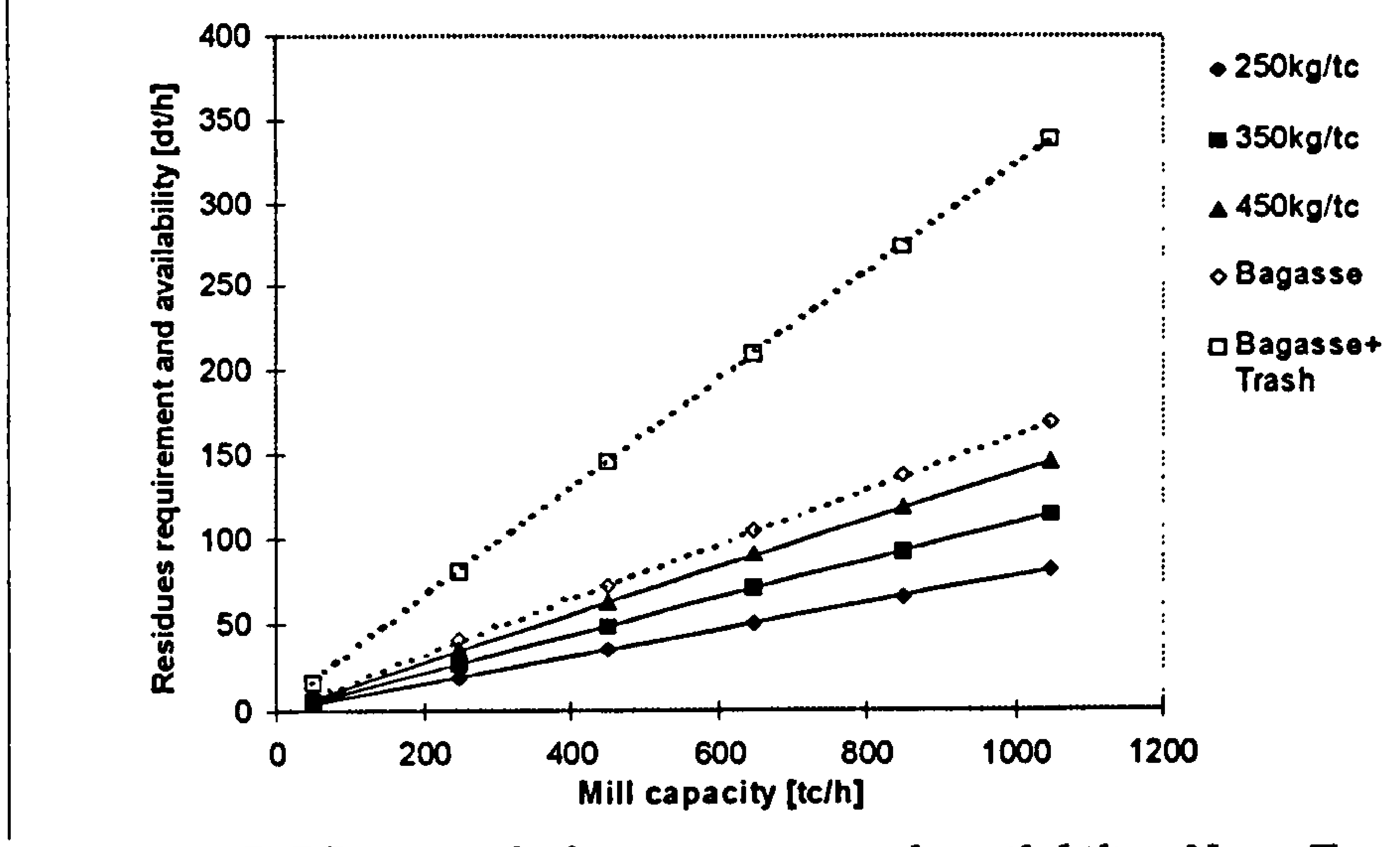

Figure 28: HP-BIG/CC system fuel requirement and availability. Note: Trash means harvest residues

The graph shows that the different process steam requirements could be satisfied by the available bagasse for the systems and capacities considered. Harvest residues provide an additional source of fuel and increase fuel availability. In our case, where the process steam requirements can be met by the available bagasse, the harvest residues could be used outside the harvest season to increase the plant load and generate additional power for export to the grid. The surplus electricity generated during and outside the harvesting season is calculated as being 180 kWh_e/tc and 234 kWh_e/tc, respectively. Annual surplus electricity production from year round operation based on bagasse and harvest residues would then be about 414 kWh_e/tc. As a comparison, surplus electricity from high pressure boilers coupled to condensing-extraction steam turbines is estimated to be between 80 and 100 kWh_e/tc considering only bagasse use during the milling season, and about 220 kWh_e/tc if harvest residues are considered for year round operation (Larson and Williams, 1990).

The use of harvest residues outside the milling season presents advantages for a fuel cycle based on sugarcane residues. The harvest residues could be collected, baled and stored at the edge of the fields during the harvesting season and could then be transported, stored and converted at the processing plant outside the harvesting period, limiting thus the need for additional infrastructure (i.e. trucks, storage space). During the milling season, harvest residues may need to be used to compensate for bagasse exports to satisfy other industries' energy needs (e.g. the orange juice and ceramics industry in the State of São Paulo). Also, depending on the gasification characteristics, bagasse and harvest residues fuel mixing may be desirable to a certain degree (e.g. to lower the alkali content of the biomass fuel).

5 The framework for biomass energy in Brazil

The exploitation of the large sugarcane residues potential discussed above will very much depend on future energy demand and supply trends, on the regulatory and policy framework, as well as on the attitude of the key players involved.

5.1 An overview of energy demand and supply

Renewable energy plays an important role in Brazil and satisfies about 70% of the country's primary energy needs, mainly in the form of hydropower, the remaining 30% being satisfied by fossil fuels. Wood and sugarcane products account for about 12% and 14% of the primary energy, respectively (BEN, 1998). The pulp & paper, agro-industry (including sugar and alcohol industry) and the steel industry are the major consumers of biomass energy. In 1997, alcohol production in Brazil provided 14.4% of the primary energy used in the transport sector, corresponding to about 6.7Mtoe and representing about 40% of the fuel energy used in light vehicles (BEN, 1998). Although the absolute contribution of alcohol has been gradually increasing, its relative contribution has been decreasing substantially. Most industrial uses of biomass energy are to satisfy the own industries' energy demand, heat in particular. In 1997 only 5% of the bagasse was used to produce surplus electricity (BEN, 1998). There remains a large unexploited biomass energy potential.

Energy demand is rising in Brazil, requiring increased inputs of primary energy and the installation of additional generating capacity. Over the last years electricity consumption in Brazil has grown at a rate of about 6% annually. In its 1996 ten year plan ELECTROBRAS indicated that Brazil needs to increase its generating capacity by about 3.2 GW per year (ELECTROBRAS, 1996). Deregulation, privatisation and market forces may in the long-term favour the penetration of renewable energy other than large hydro which has been so far the main renewable energy source. However, the short-term tendency is towards an increased use of fossil fuels (e.g. natural gas) because of the lower cost associated with power generation from fossil plants compared to alternatives (e.g. hydro, nuclear, renewables). In particular, plans for several large hydroelectric schemes have been delayed. Hydropower potential is large in Brazil, with only about 20% of it being exploited. About two thirds of the remaining potential is estimated to be situated in the Amazon region and far away from the main energy consumption centres.

The expansion of the power generating capacity in Brazil using fossil fuels (natural gas and coal) would result in significant externalities, in particular related to impacts on human health deriving from emissions of pollutants at the conversion stage and to the impacts of greenhouse gases emissions. The magnitude of the externalities would depend on the fuel and technology used and on the siting of the facilities.

Additional large hydroelectric schemes are also likely to result in significant externalities. In the Amazon region, 'hydroelectric flooding' is considered a potentially large source of greenhouse gas emissions resulting from biomass decay. However, Rosa and Schaeffer (1995) arrive at the conclusion that, although hydropower plants may be important sources of greenhouse gas emissions, they remain in most cases a better option than fossil based thermoelectric power generation with respect to climate change. Fearnside (1996) believes that the picture, in particular in the Amazon region, is likely to be worse than that presented by Rosa and Schaeffer, and criticises their study because of its neglect of CO_2 emissions (only methane is considered), lack of discounting and supposedly optimistic power outputs per unit of flooded area. Large hydropower schemes may also have significant environmental impacts on terrestrial and aquatic ecosystems, as well as social impacts (e.g. displacement of indigenous populations) (Moreira and Poole, 1993; Fearnside and Barbosa, 1996a and b and Rosa et al., 1988). Therefore, there is reason to believe that, besides the high investment costs, large hydroelectric schemes, in particular in regions such as the Amazon, may also have significant external costs. Brazil also possesses a large potential for small hydropower schemes which may present less economic and environmental problems compared to large schemes.

Brazil is a large contributor of greenhouse gas emissions, mainly as a result of deforestation. Deforestation related CO_2 emissions in 1991 were estimated at 150-220Mt of carbon per year, while 1990 energy consumption related CO_2 emissions were estimated at 73Mt of carbon per year (La Rovere et al., 1994). However, the CO_2 emissions from the energy and transport sector on a per capita basis are low compared to other countries because of Brazil's level of economic development and of the important renewable energy contribution to primary energy use. However, energy demand in Brazil, in particular in the form of electricity and transport fuels, is likely to grow considerably, and so will CO_2 emissions, given the current trend to install fossil fuel based generating capacity and the stagnation of alcohol use in vehicles. The renewable resources are nevertheless available which could avoid a considerable portion of the emissions.

5.2 A rapidly evolving framework

The Brazilian energy sector is undergoing some profound transformations. In 1995 the Brazilian government decided to privatise the electricity sector. The privatisation process has lead to a series of regulatory changes, and laws have been introduced with regard to the establishment of a regulatory agency, independent power producers, choice of suppliers, access to transmission and distribution grids, and a wholesale market. The urgency to privatise has pushed regulatory changes, but changes in energy policy and planning are lagging.

Electricity sales to the interconnected system have been authorised since 1989 through long and short-term contracts with the electricity utilities based on estimates for the long and short-term marginal cost of generation. However, the contribution of self-generators and independent power producers to the grid has been very low for a variety of reasons amongst which the market power exerted by the electricity utilities offering unfavourable grid access and electricity purchasing conditions and the generally unfavourable Brazilian economic situation hindering investment. In the state of São Paulo, only the Usina Santa Elisa and Usina Vale do Rosario had long-term contracts at R\$38/MWh$_e$[13]. Other mills supply surplus electricity, based on yearly contracts, at a price of up to R\$13/MWh$_e$ (Gazeta Mercantil, 8/10/97).

A 1996 law ensures that self-producers and IPPs have open access to the grid through the payment of transmission and distribution fees. This is a significant step, however criticism has been expressed over the fees being too high and not reflecting marginal costs. Also, electricity distributors are gradually being freed from long-term supply contracts with state owned utilities. Legislation has been issued by which from 2003

[13] 1 R\$ = 0.71 € = 0.93 US\$ (1995)

electricity distributors will be able to negotiate freely 25% of the contracted electricity volume and the percentage will rise gradually until 2006 when all contracted electricity will be negotiated freely (Gazeta Mercantil, 9/3/98).

Ideally the introduction of an electricity spot market should send price signals reflecting the short-term marginal cost of electricity supply, and other institutional changes should send price signals reflecting opportunity costs. These should contribute to more informed decision-making. In the past, electricity utilities have exerted their market power by imposing high tariffs to self-producers for back-up power supply thus discouraging self-generation. A liberalised market, where self-generators can acquire back-up power through bilateral arrangements or on the spot market, should favour self-generation. The regulatory changes are still underway, with ANEEL - the national electrical energy regulatory agency - still addressing a variety of issues and shaping the regulatory framework, and the effects of the ongoing changes are yet to manifest themselves fully.

At present, co-generation and generation from renewable energy sources do not benefit from financial incentives, possibly reflecting their social benefits, except for small hydroelectric schemes (<30 MW). These are granted access to any consumer with a demand greater than 0.5 MW - current legislation otherwise states that consumers can freely choose their supplier for demands greater than 10 MW for existing consumers and 3 MW for new ones - and are dispensed from half the transmission grid use fee. Furthermore, coal and diesel generation receive a subsidy (Conta de Consumo de Combustivel), currently being phased out, to cover the higher generating cost compared to the average cost of electricity (Gazeta Mercantil, 9/2/98).

There are indications that environmental and sustainability issues are likely to play an increasing role in future regulation through the enforcement of command-and-control measures and through the introduction of financial mechanisms (Bajay et al., 1999). Possible support schemes include: premium price electricity payments, capital subsidy, soft or semi-commercial loans, assistance in feasibility studies. Changes are also taking place at the state level. For example, the state of São Paulo has been addressing, through recent actions and legislation, issues related to energy conservation, emissions reductions and sustainable energy sources for the future. Also, public awareness on environmental issues has been rising, an example of which has been the growing opposition to the burning of sugarcane fields prior to harvesting.

There has been interest on the part of foreign investors in electricity generation in Brazil, in particular natural gas fuelled thermoelectric plants. However, co-generation and small-scale independent power generation are also attracting the attention of foreign investors. Rolls Royce Ventures, for example, plans to invest US$120 million for a total installed electrical capacity of 180MW (150 MW industry based co-generation and 30 MW independent power generation) (Gazeta Mercantil, 13/2/98). Electricity market restructuring and privatisation is likely to favour co-generation in the long-term. However, until the regulatory picture becomes clear investment is likely to remain low.

5.3 Key players

The key players affecting the exploitation of sugarcane residues for electricity generation are the sugarcane processing plant owners (which are usually also large sugarcane producers), sugarcane industry associations, financial institutions, the local and national governments and to a certain extent the public.

It is up to sugarcane processing plant owners and possibly independent power producers to exploit the electricity potential of sugarcane residues. Investors will base their decision on the economic profitability of the project in terms of rate of return. From an economic point of view it would be most preferable to generate surplus electricity on-site at the sugarcane processing plant rather than at a different site. Mill owners would therefore have to invest in co-generation equipment or third parties (e.g. IPPs) could become involved in the co-generation scheme in a variety of ways, for example by taking in charge on-site co-generation and selling steam and electricity to the processing plant or by a uniquely financial participation. Diversification of the sugar and alcohol industry may be a key component to its economic competitiveness and sustainability. Revenues from electricity sales could reduce alcohol production cost, making it thus more competitive with competing fuels of fossil origin (Williams and Larson, 1993).

However, beside the question of economic profitability there are a series of other issues and possible barriers. The sugarcane industry is a very traditional, often family owned business, which has shown to be slow in adopting technological innovation. Electricity generation will involve an expertise and a business strategy outside those of the sugarcane processing industry. The technological innovation, business adaptation and interaction with third parties which may be required may themselves be barriers to enhanced co-generation. The cost of capital in Brazil is very high and unless greater economic stability and lower interest rates are achieved, investment by industry in such schemes appears extremely unlikely.

Given a more favourable economic climate, national development banks and international financial institutions could contribute to the financing of co-generation schemes e.g. soft loans. Local and national governments have an important role to play in setting an adequate and clear regulatory, policy and planning framework. Sugarcane industry associations also have an important role to play in supporting the demonstration of viable schemes and in providing information to their members. Finally, the public, through its quest for more sustainable energy sources and more environmentally sound industrial practices has a role to play in influencing policy-making which may favour co-generation from sugarcane residues.

6 General regional information

Air quality in the state of São Paulo is a reason for concern. In particular, urban air quality issues related mainly to pollution from transport in large cities such as São Paulo have attracted considerable attention. However, pollution from industrial sources is also an issue (e.g. the refining complex in Cubatao). Lack of adequate emission standards and poor enforcement have resulted in high emissions from industrial processes and the sugarcane processing industry is likely to be no exception (e.g. NO_x, particulate and CO emissions), but no detailed emissions inventory is available. In the case of the sugarcane industry, attention has although focused on the emissions from the burning of the sugarcane fields prior to harvesting, which has been found to impact on human health and amenity (e.g. visibility and damages to buildings) (AgroFolha, 1997). In recent years public opposition to the burning of sugarcane fields has been growing.

Water courses are also often polluted by industrial and municipal sources. The sugarcane industry is a significant source of water pollution through the discharge to water courses of water used in the cane washing process and through the disposal of waste products (e.g. vinasse) from the alcohol distillation process (Cortez et al., 1998).

The run-off and percolation of vinasse may affect water bodies through excess concentrations of nutrients such as N, P and K, and lead to impacts on human health and to the eutrophication of water bodies. Also, water abstraction contributes to the depletion of water courses and exacerbates pollution problems.

Since 1975, the sugarcane planted area has increased significantly, in particular in the state of São Paulo. The monoculture may have impacts on soil quality, on biodiversity and on the landscape, apart from other environmental impacts which depend on agricultural practice (e.g. pesticide and fertiliser application). The effects of sugarcane cultivation and processing on water bodies may be more evident than the long-term effects on soil quality and biodiversity. However, vinasse application may affect the chemical stability of the soil and the life of organisms, from micro-organisms to insects and other small animals. Sparovek and Lepsch (1993), in a study carried out in the Piracicaba region in the State of São Paulo, indicate that land dedicated to sugarcane culture has increased by about 15% since the early 1960s and that it represents about 50% of land use in the region. They express concern over the fact that about 48,000 ha (27% of the total area comprised in the study area) is exposed to a high risk of degradation because of over exploitation, mainly from sugarcane plantations.

The sugarcane industry has been slow in adopting new and clean technologies and practices. However, important changes are expected in the coming years, driven by industrial competitiveness and regulation. Also, greater public awareness has been influencing government policies towards changes in practices, in particular concerning cane harvesting and washing.

The sugarcane industry is a major employer in Brazil, in particular in the state of São Paulo. Estimates of direct employment figures for Brazil vary between 600,000 and 1 million people. It has been estimated that about 140,000 people are employed for manual cane harvesting in the state of São Paulo (Cortez et al., 1998). These jobs are seasonal and the working conditions very poor, their preservation is then not necessarily socially beneficial. Nevertheless, the social impacts of mechanisation need careful consideration, as many seasonal jobs will be lost (some 70,000 jobs in the state of São Paulo alone, assuming mechanical harvesting of half of the sugarcane fields). What is needed is a gradual transition to mechanical harvesting accompanied by investments in other economic sectors which can absorb the workforce and offer better occupational conditions.

7 Gasification-based co-generation at sugarcane processing plants

This section provides a detailed description of the fuel cycle for gasification-based co-generation at sugarcane processing plants fuelled with sugarcane residues (bagasse and harvest residues). An in-depth knowledge of the fuel cycle is essential to the economic, environmental and resource use analysis of Chapter 7 which leads to key considerations on the viability of the exploitation of the potential resource.

7.1 Description of the fuel cycle

The use of sugarcane residues for co-generation involves four principal stages: residues collection, transport and conversion, and waste disposal. Table 42 shows the activity groups and activities within the system boundaries, on which the fuel cycle cost, labour, environmental impact and resource use calculations are based. The fuel cycle boundaries must be defined so that they include all activities leading to significant resource use and environmental impacts.

Table 42: Sugarcane residues fuel cycle summary

Production	Transport (On-road)	Conversion	Waste disposal
Bagasse: Waste product at mill site Trash: Windrowing* Baling In-field transport	Truck (15-30t) Distance: a function of mill capacity (e.g. 12km for 300tc/h mill)	LP(HP)-BIG/CC	Recycling/Landfill

*the piling of residues in long rows ready for baling

In the case of bagasse, it appears suitable to define the system boundaries so that no impacts from the sugarcane production cycle are considered, all impacts being attributed to the production of sugar and alcohol. In the case of sugarcane harvest residues, the system boundaries will consider all activities and impacts related to its collection and transport. It is still a matter of discussion as to what portion of sugarcane residues should be left in the field for agronomic reasons. Both an excessive and insufficient removal of residues may have negative impacts on soil and water and on sugarcane growth. Good practice in the collection of residues is likely to avoid any significant impacts from machinery use (e.g. soil compacting). The impacts of road transport need to be considered carefully because of the important quantities of sugarcane already transported, and impacts could be mitigated by transporting harvest residues outside the harvesting season. Emissions from the collection and transport of the residues may be significant. In particular, collection and transport will contribute some net CO_2 emissions to the fuel cycle.

7.1.1 Residues collection, in-field storage and transport

Bagasse is produced at the mill and can be stored on-site. It is then a readily available source of fuel. The use of harvest residues will require the introduction of logistics for their collection, storage and transport.

Following the mechanical harvest of unburned cane, residues, consisting of cane tops and leaves, are left in the field as a more or less uniform cover. In the higher productivity regions in the south-eastern part of Brazil typical cane stalk yields are close to 90 tc/ha resulting in about 14.5 odt(harvest residues)/ha. The residues are likely to enhance soil fertility, prevent soil erosion, help the soil to retain moisture and inhibit the growth of weeds. However, large amounts of residues left in the field also render more difficult crop establishment and maintenance activities. Paradoxically, in some cases more inorganic fertiliser may have to be applied to the field if large quantities of residues prevent it from reaching the soil. Excessive quantities of residues may also negatively affect cane growth in the first year after harvesting. Therefore, apart from their interest as a fuel, it may be desirable to remove a fraction of the residues from the fields for agronomic purposes.

Very little experience exists worldwide on the collection and use of sugarcane residues left in the field after harvesting and the collection and transport activities are assumed to be in many ways similar to those typical of straw. The data used in this study is based on equipment used for straw collection and on the limited tests carried out to date on sugarcane residues collection (e.g. tests carried out by COPERSUCAR and at the Usina Santa Elisa, in the state of São Paulo).

Following the harvest, the residues should be left to dry in the field for a few days. The moisture content of the harvest residues can be lowered to about 35% by letting them dry in the fields for 4 to 6 days prior to collection (Kadyszewski, 1991). Then, variable fractions of the residues can be raked into windrows and subsequently baled (large square bales 120x120x70 cm, weighing about 220 kg are considered in this study). Tests carried out by COPERSUCAR indicate that large rectangular bales are preferred to small rectangular bales or round bales because of greater ease of operation and more efficient collection and transport. Windrowing prior to baling increases the operational efficiency and reduces the risk of damage to the collection system from contact with the ground (CENBIO, 1998b).

The bales are then transported to the edge of the field, to a suitable location for future truck loading, and stored in piles which should be covered or arranged in such a way as to limit the infiltration of water in the case of rain. Rectangular bales appear to be more sensitive to degradation compared to round bales, and will require some form of protection if stored in the fields. If adequate precautions are taken, further drying of the bales will occur during storage. When required, the bales are loaded on a truck, using a bale handler, and transported to the conversion facility where they are unloaded and stored prior to use as fuel. Limited experience in the collection and transport of the residues has shown that particular attention must be paid to the scheduling of operations, the prediction of possible equipment down times and bottlenecks which may occur in transport.

No conclusive studies exist on the amount of residues which could be removed from the fields without negatively affecting soil quality. It is however likely that, if a suitable amount of residues is left in the fields, soil quality will improve compared to the present situation in which pre-harvest burning of the fields is common practice. A proper management of the residues is also likely to lead to lower inputs of inorganic fertilisers.

Atmospheric emissions will result from the activities associated with the collection and transport of the residues. Also, the transport of bales to the mill will increase traffic on roads which are already heavily used by trucks transporting sugarcane and bagasse which is exported from the mills. However, if residues were to be used to generate electricity outside the milling season, then transport as well could occur at that time, and would not contribute additional transport during the harvesting season. The use of residues outside the milling season is principally of interest as it would contribute to the economic viability of the system because of investment in smaller generating capacity and increased annual operation, compared to a generating facility which would make use of bagasse and harvest residues during the harvesting season. Also, additional investments could be avoided (e.g. trucks used to transport the sugarcane during the harvesting season could be used to transport the residues outside the harvesting season) and little or no additional storage space to that foreseen for bagasse would be required at the processing plant.

Data on materials, machinery and labour employed in the collection and transport of the residues is used in the cost, emissions and resource use calculations. The cost of diesel in Brazil is taken as R$0.46/l (€0.33/l) and the labour cost for machinery operation is estimated to be between R$5.0 and R$6.7 per hour (between €3.5 and €4.7 per hour) (JornalCana, 1997). The cost of transporting the bales is assumed to be the same as that for transporting sugarcane stalks and is estimated at R$2.4/km (€1.7/km) (JornalCana, 1997). This cost does not include costs associated with loading and unloading which are accounted for separately by providing data on the machinery, labour and activity time required. Energy inputs and atmospheric emissions calculations also require data specific to the machinery and activity times. The characteristics of the machinery employed in residues collection and transport and the activity times are discussed in Annex 1. The average transport distance for sugarcane residues to the processing plant is estimated based on the residues yield and land area destined to sugarcane cultivation around the plant. Average transport distances in the case of the Usina Ester and the Usina Vale do Rosario are 14 km and 22 km, respectively.

7.1.2 Residues conversion and ash disposal

Air-blown circulating fluidised bed gasification (CFB) appears well suited for the conversion of the biomass fuel in question, in particular due to its tolerance to possible variation in fuel quality and the high fuel throughput which can be achieved. Also, the coupling of the gasifier to gas and steam turbine combined cycles will result in high generating efficiencies and low emissions.

The conversion facilities considered for co-generation would be similar to the HP-BIG/CC demonstration plant in Värnamo, Sweden, or to the planned LP-BIG/CC demonstration plants (e.g. the ARBRE Power Plant in Yorkshire, UK, and the Brazilian Wood BIG-GT Demonstration Project in Bahia, Brazil (Waldheim and Carpentieri, 1998). Some modifications (e.g. equipment to shred the bales) will be required for the systems to operate on sugarcane residues in place of wood chips.

Very little experience exists on the gasification of sugarcane residues. Limited laboratory scale tests with bagasse and sugarcane harvest residues in CFB gasifiers have, however, produced promising results (TPS, 1997). Feeding problems associated with the low density of the fuel could be overcome by the selection of appropriate feeding equipment (e.g. screw-piston feeders). The presence of ammonia in the fuel gas, resulting from the nitrogen present in the biomass fuel, could lead to undesirably high NO_x concentrations in the gas turbine flue gas. Means to reduce the ammonia content of the fuel gas could be adopted (e.g. catalytic bed material, use of acidic solution in wet gas scrubbing). The presence of chlorine in the fuel gas could also be of concern because of possible corrosion to equipment downstream of the gasifier. Chlorine could be washed out in the wet gas scrubber or absorbed by catalytic bed materials (e.g. dolomite). The greatest concern is caused by the silica and potassium contents of the ash which could lead to the formation of eutectics with melting points lower than the gasifier operating temperature. Ash melting and sintering would lead to gasifier operating problems, and reducing the operating temperature would result in reduced carbon conversion efficiency. It is difficult to predict to what extent ash melting and sintering will be a problem. The high reactivity of sugarcane residues and, even the possible catalytic activity of potassium, could allow for lower operating temperatures without an important reduction in carbon conversion efficiency. Also, additives such as dolomite may act as a remedy to the formation of low melting point eutectics. To assess the suitability of sugarcane residues as fuels for CFB gasification it is necessary and crucial to carry out extensive testing. Pilot scale testing of bagasse and sugarcane harvest residues is envisaged as part of an extension of the Brazilian Wood BIG-GT Demonstration Project (TPS, 1997 and CENBIO, 1998a).

Ash from the combustion of bagasse is currently recycled to the fields as a fertiliser and the same is expected to occur for the gasification of bagasse and harvest residues. The transport and spreading of the ash on the fields has not been included in this study as they are considered activities related to sugarcane production. Furthermore, the impacts of such activities are small compared to those of the other stages of the fuel cycle.

8 Reference fuel cycles

A gas pipeline transports natural gas from Bolivia into Brazil. Since the introduction of the pipeline several plans for natural gas fuelled thermoelectric plants have been proposed. The low capital costs and short lead times which characterise natural gas fuelled combined cycle plant compared to more conventional alternatives make them particularly attractive. CCGT plants are likely to play a significant role in future electricity supply, in particular in the South of Brazil, and they have been chosen as the reference conversion technology for electricity supply in the present study.

Gasification–based co-generation will then be compared to a system composed of a conventional combustion-based co-generation system to satisfy the heat and electricity needs at the mill and a CCGT system to supply an equivalent amount of electricity to the surplus electricity generated by gasification-based co-generation. Table 43 provides the energy breakdown for the Brazilian reference system in order to supply the same energy as BIG/CC co-generation plants.

Table 43: Energy breakdown for Brazilian reference system

	Energy	Exergy
Heat from bagasse fuelled combustion-based co-generation	0.45	0.26
Electricity from bagasse fuelled combustion-based co-generation	0.02	0.03
Electricity from CCGT	0.53	0.71

The specific emissions of the different stages of the fuel cycles of the systems considered are provided in Annex 1. Emissions from the CCGT-based reference fuel cycle for Brazil are assumed to be the same as the CCGT-based reference fuel cycle emissions for the UK (see Section 7 in Chapter 4).

9 Conclusion

Sugarcane residues represent a large energy potential. Current use of bagasse is inefficient and there is a large potentially exploitable residue in the form of cane tops and leaves, referred to as harvest residues. The total energy content of sugar cane residues is estimated at about 1634 PJ, of which about 1026 EJ is estimated to be practicably exploitable based on assumptions on harvest residues recoverability.

The use of BIG/CC conversion systems would allow for significant amounts of surplus electricity generation at the sugarcane processing plant sites. The surplus electricity generated during and outside the harvesting season is calculated as being 180 kWh_e/tc and 234 kWh_e/tc respectively. Annual surplus electricity production from year round operation based on bagasse and harvest residues would then be about 414 kWh_e/tc. This is about double the surplus electricity that could be obtained using condensing-extraction steam turbines. Extending the operation of the generating plant outside the milling season significantly improves the economic viability of the system. This surplus electricity can contribute significantly to future electricity supply in Brazil with significant economic and environmental benefits.

Energy demand, in particular electricity, is growing rapidly in Brazil. Surplus electricity from gasification-based systems fuelled with sugarcane residues can play an important role in meeting future energy demand. While the short-term economic competitiveness of BIG/CC systems fuelled with sugarcane residues remains an issue, these systems are likely to possess environmental, resource use and possibly social advantages which should be considered in future policy and decision making.

So far the energy market structure has provided little incentive to the generation of surplus electricity from sugarcane residues. However, this may change in the future through the introduction of regulation aiming at fairer pricing structures in the electricity market, as well as planning and policies taking into consideration issues such as the environment, non-renewable resources use and energy security and sustainability.

Financial barriers are a major issue in the development of co-generation and a more stable economic environment favouring investment is an important prerequisite. Financing schemes and possible economic incentives require further attention. A number of other non-technical barriers hinder the development of enhanced co-generation in the sugarcane industry, and successful demonstration projects and dissemination of information on the potential of co-generation could help reduce the barriers. Stricter regulations on emissions are likely to increase the costs of conventional co-generation at the mill sites, as well as the costs of energy generation in general, favouring the economic viability of cleaner technologies (e.g. BIG/CC) and processes.

Some of the potential benefits associated with BIG/CC systems fuelled with sugarcane residues are: diversification and increased economic sustainability of the sugar and alcohol industry, reduced need for investment in power generation, reduced expenditure on fossil fuel imports, reduced need for high voltage transmission, reduced environmental burden compared to fossil electricity and possibly to large-scale hydroelectricity, and consequently a contribution to a more sustainable energy supply system.

The detailed description of the fuel cycles emphasises technical uncertainties and aspects requiring particular attention. It also provides key information for the economic and environmental analysis presented in Chapter 7. The weakest links in the fuel cycle discussed are the lack of experience on the procurement of sugarcane harvest residues (bagasse is readily available at the plant site) and on the gasification of sugarcane residues. More information is also required on agronomic aspects related to the presence of harvest residues in the fields. The fuel cycles present no major technical barriers, but some particular activities may present problems or could be improved. Some issues will have to be dealt with in relation to the storage of bales of harvest residues, pre-treatment and feeding of bagasse and harvest residues, product gas quality in relation to trace elements such as alkali metals (Na and K) and chlorine, and silica and potassium present in the ash, which could lead to low ash melting points.

In the case of sugarcane residues, the priority impact categories are likely to be associated with atmospheric emissions from the different fuel cycle stages. The priority impact categories considered are then essentially: human health, acidification impacts, climate change impacts and resource use.

The following chapter provides a detailed economic, environmental and resource use analysis of the sugarcane residues-fuelled BIG/CC fuel cycle and its assessment in relation to the reference systems described above.

CHAPTER 7

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF THE BRAZILIAN CASE STUDY

1 Introduction

The scope of this chapter is to provide a detailed economic, environmental and resource use analysis of the gasification-based biomass fuel cycles fuelled with sugarcane residues. The economic, environmental and resource use performance of the gasification-based biomass fuel cycles is assessed relative to the reference systems defined in Chapter 6. The quantitative results presented are based on a spreadsheet database and model developed to calculate the private costs (base year 1995), employment, emissions and non-renewable energy use inventories associated with the biomass and reference systems (see Annex 1 for details).

2 Economic analysis

The following sections present a detailed private costs analysis for the sugarcane residues fuel cycle, as well as an estimation of the direct employment generated. The next chapter (Chapter 8) will discuss the external costs of the fuel cycle.

The costs, emissions, energy balance and employment associated with the fuel cycle are assessed based on a fuel cycle activities inventory database and model (Annex 1). The private costs calculated consist of the direct costs of the fuel cycle activities which intrinsically account for all indirect costs. Direct and indirect energy requirements are estimated. Direct energy requirements consist of the fossil fuel input for machinery operation during fuel cycle activities and the energy required for the construction of the conversion plant. The indirect energy requirements accounted for consist of the energy embodied in equipment used. Only direct emissions to air are accounted for in this study, and emissions to soil and water are discussed. Direct employment is also estimated based on the specific requirements of the activities involved in the fuel cycle.

2.1 Private costs analysis

The detailed private costs analysis discusses the costs of the different stages of the co-generation from sugarcane residues fuel cycle, as well as the full fuel cycle cost of energy.

2.2 Residues collection and transport costs

Costs for sugarcane harvest residues delivered to the plant gate have been calculated as a function of mill capacity and discount rate, based on the requirements of the activities involved in residues collection and on transport distance estimates (Annex 1). Average harvest residues transport distances are estimated to range between 5 km for a 50 tc/h mill and 25 km for a 1050 tc/h mill (these transport distances are likely to be conservative as they assume that all land around the mills is cultivated with sugarcane). The costs calculated range between €1.22/GJ for a 50 tc/h mill and 5% discount rate and €1.73/GJ for a 1050 tc/h mill and 20% discount rate. Figure 29 and Figure 30 show the cost estimates. Figure 29 shows the cost ranges calculated based on two discount rates (5% and 20%) and indicates the minimum and maximum costs expected. Figure 30 shows mid-range costs calculated for different discount rates (5%, 10%, 15% and 20%). The cost range obtained may be suitable for an economically viable exploitation of the residues.

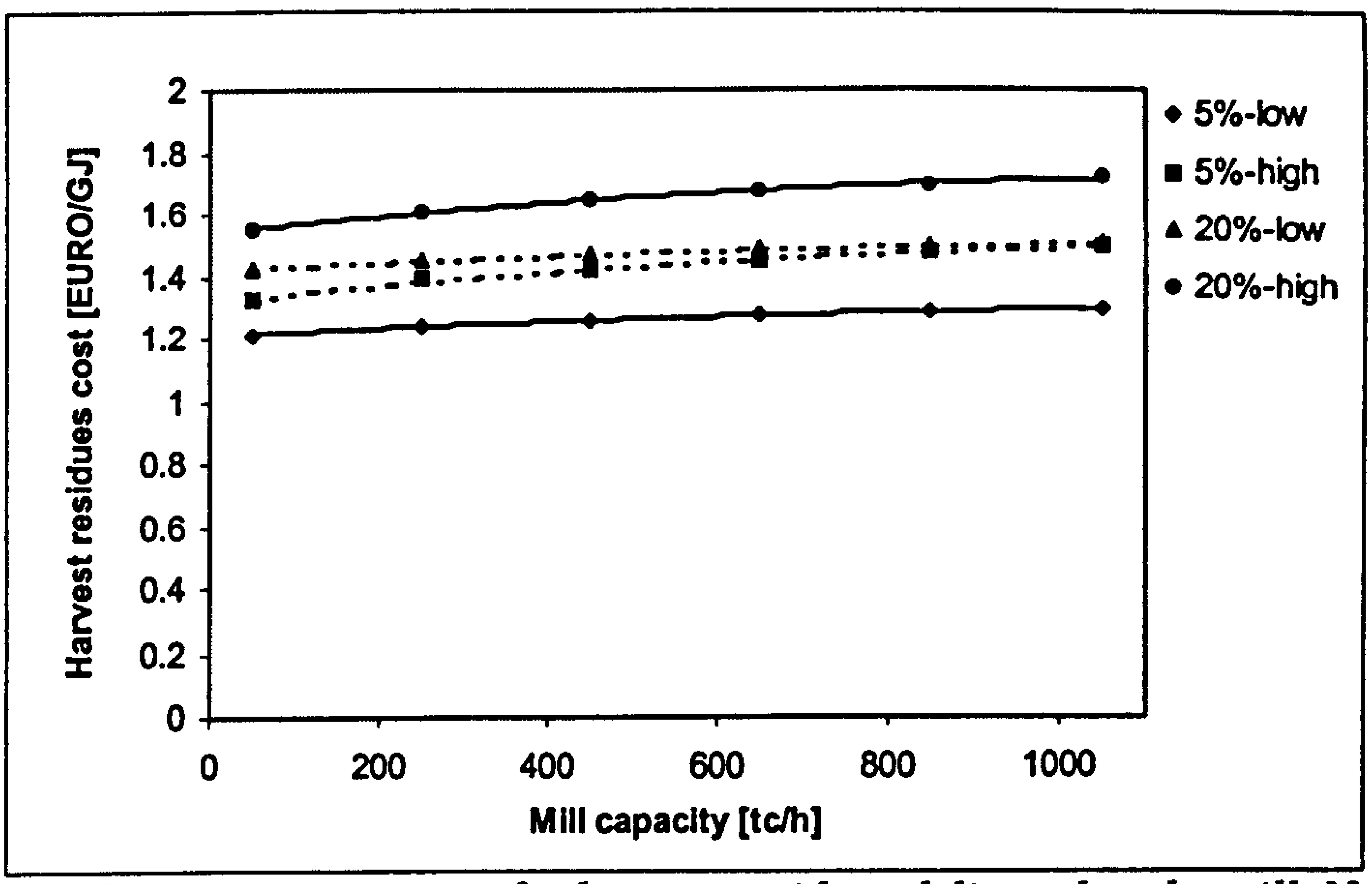

Figure 29: Cost estimate ranges for harvest residues delivered to the mill. Note: full lines are used to cost range limits

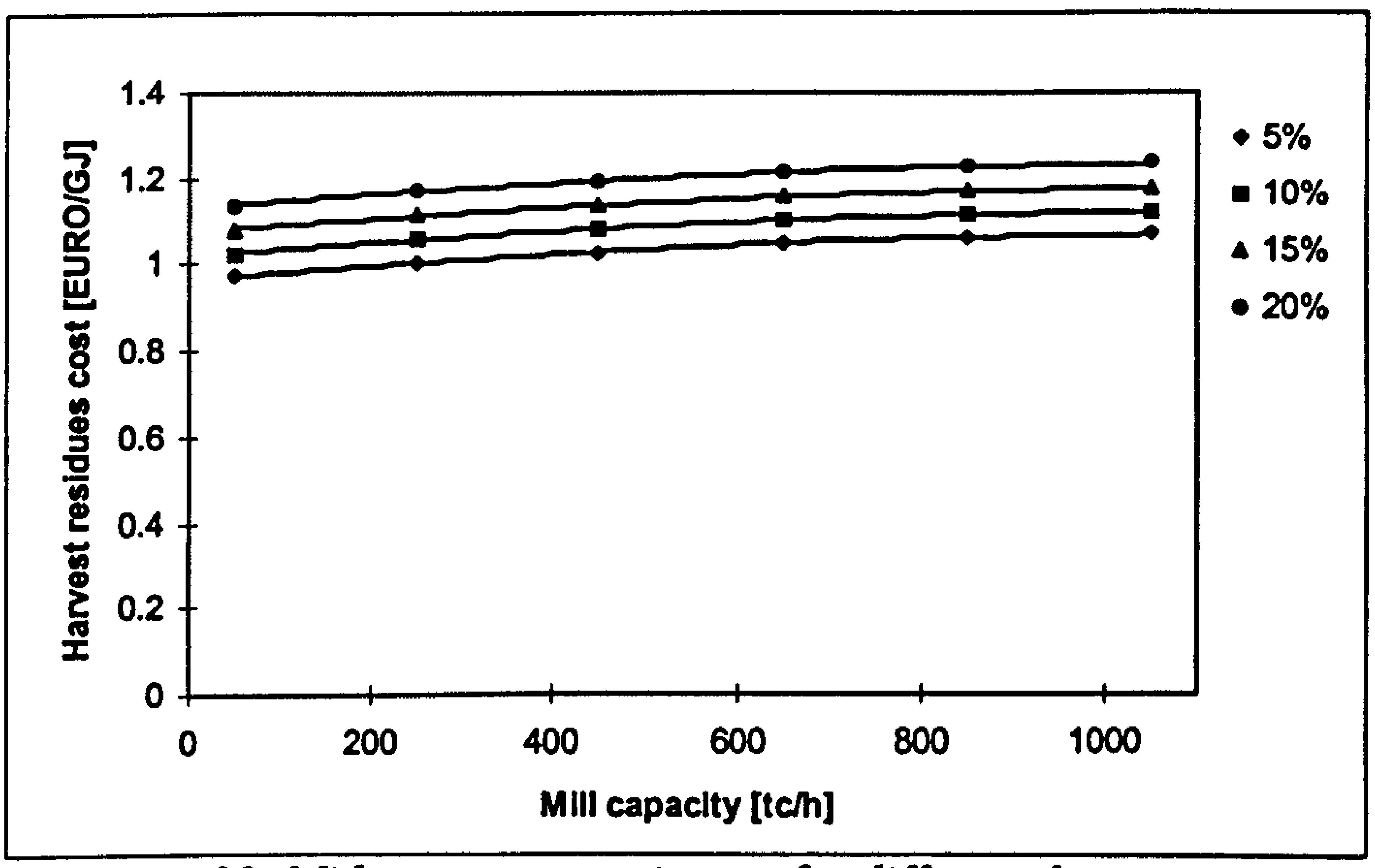

Figure 30: Mid-range cost estimates for different discount rates

Transport costs increase with mill capacity because of the larger catchment area associated with larger mills. The longer average transport distance results in about a 10% increase in the cost of residues between small and large mills.

Doubling the transport distance would result in about a 3% increase in harvest residues cost for a 50 tc/h mill and in about a 11% increase for a 1050 tc/h mill. In this case, a 14% increase in the cost of residues would result between small and large mills.

Figure 31 shows the cost breakdown for harvest residues delivered to the mill for an average sized mill (300 tc/h) and a 10% discount rate. The cost of the residues delivered to the plant is estimated at €1.31 - 1.48/GJ. Storage materials refers to the synthetic material used to cover the piles of bales, and baling material refers to twine.

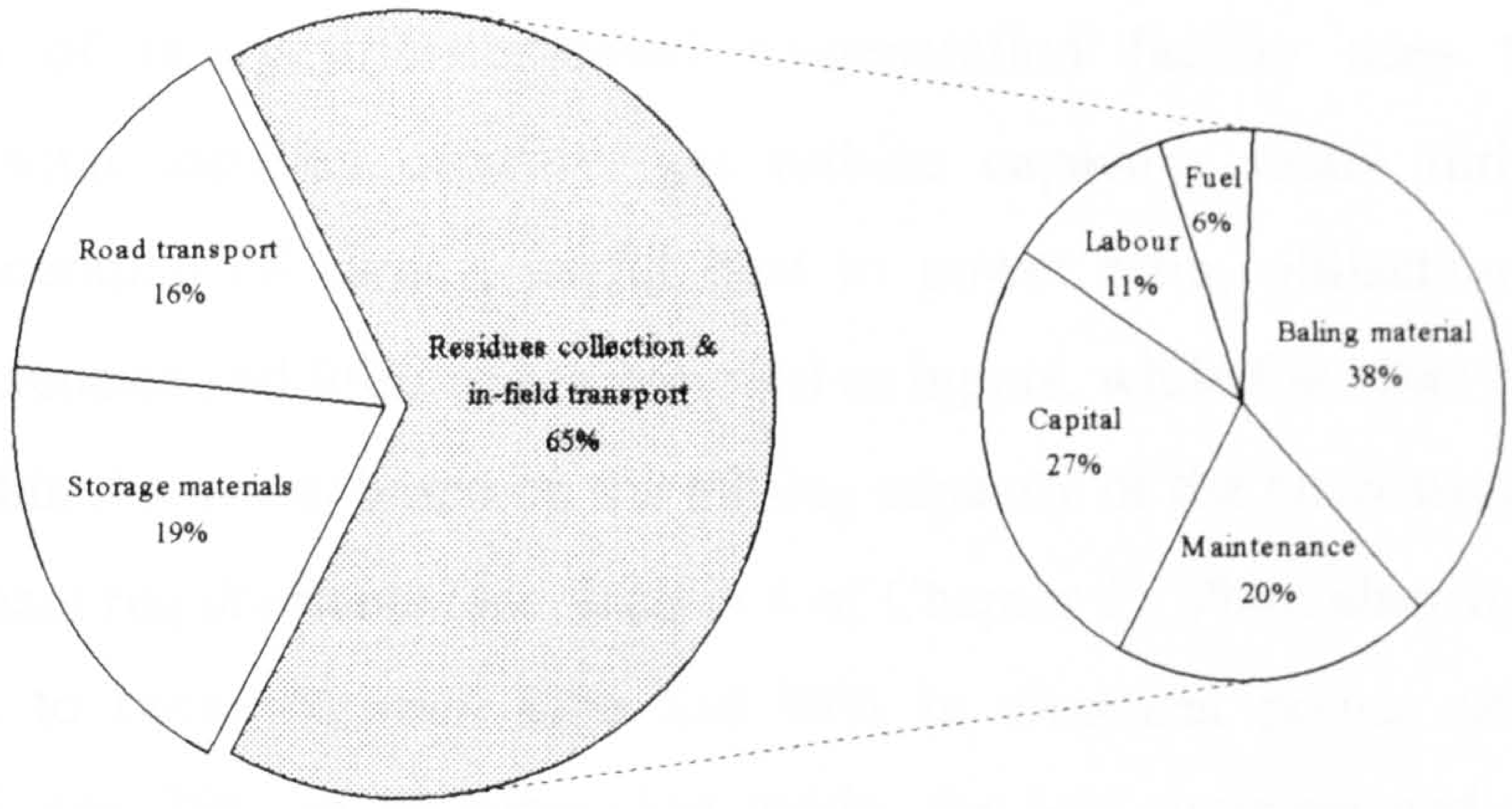

Figure 31: Harvest residues cost breakdown

Materials used in baling and storage contribute significantly to the biomass fuel cost, the importance of their reduction and of the reduction of the biomass fuel cost in general is shown in the sensitivity analysis in Section 2.3.

A more detailed look at transport costs show that they contribute between 9% and 14% of the delivered fuel costs for a 50 tc/h mill and between 10% and 17% for a 1050 tc/h mill.

Bagasse is assumed to be available at zero cost. While a fraction of the bagasse produced will possess an opportunity cost because of its use as a fuel in other industries and as a raw material for animal feed, there is no current market for most of the bagasse. To account for its alternative uses, this study imposes a limit on the bagasse which can be used as a fuel for on-site co-generation. Currently, the average bagasse export from sugarcane mills is about 10%, and the limit for its use as a fuel for on-site co-generation is then set at 90%. As an indication, the price of bagasse exported for other uses is estimated to range between €4 and €8 per tonne.

2.3 Residues conversion and energy generation costs

Co-generation plant investment costs have been calculated based on a detailed breakdown of plant equipment, design, construction and installation costs. The model that estimates the capital, operation and maintenance (O&M) and finally the generated energy costs of the gasification-based co-generation facility uses the following information: total installed capacity, gas turbine capacity, steam turbine capacity, electricity generation efficiency, useful heat to power ratio, utilisation factor, plant lifetime. Efficiencies and lifetime are provided as inputs, while the other parameters are estimated within the model based on the milling capacity of the processing plant and on its process steam requirements (see Section 4 of Chapter 6). Plant electrical efficiencies are estimated to range between 42% and 45% in electrical power only mode, and between 36% and 39% in co-generation mode, for low pressure and high pressure systems, respectively. The lifetime of the plant is assumed to be 25 years.

Figure 32 shows specific capital costs for BIG/GTCC systems as a function of mill capacity, based on expected short-term commercial developments.

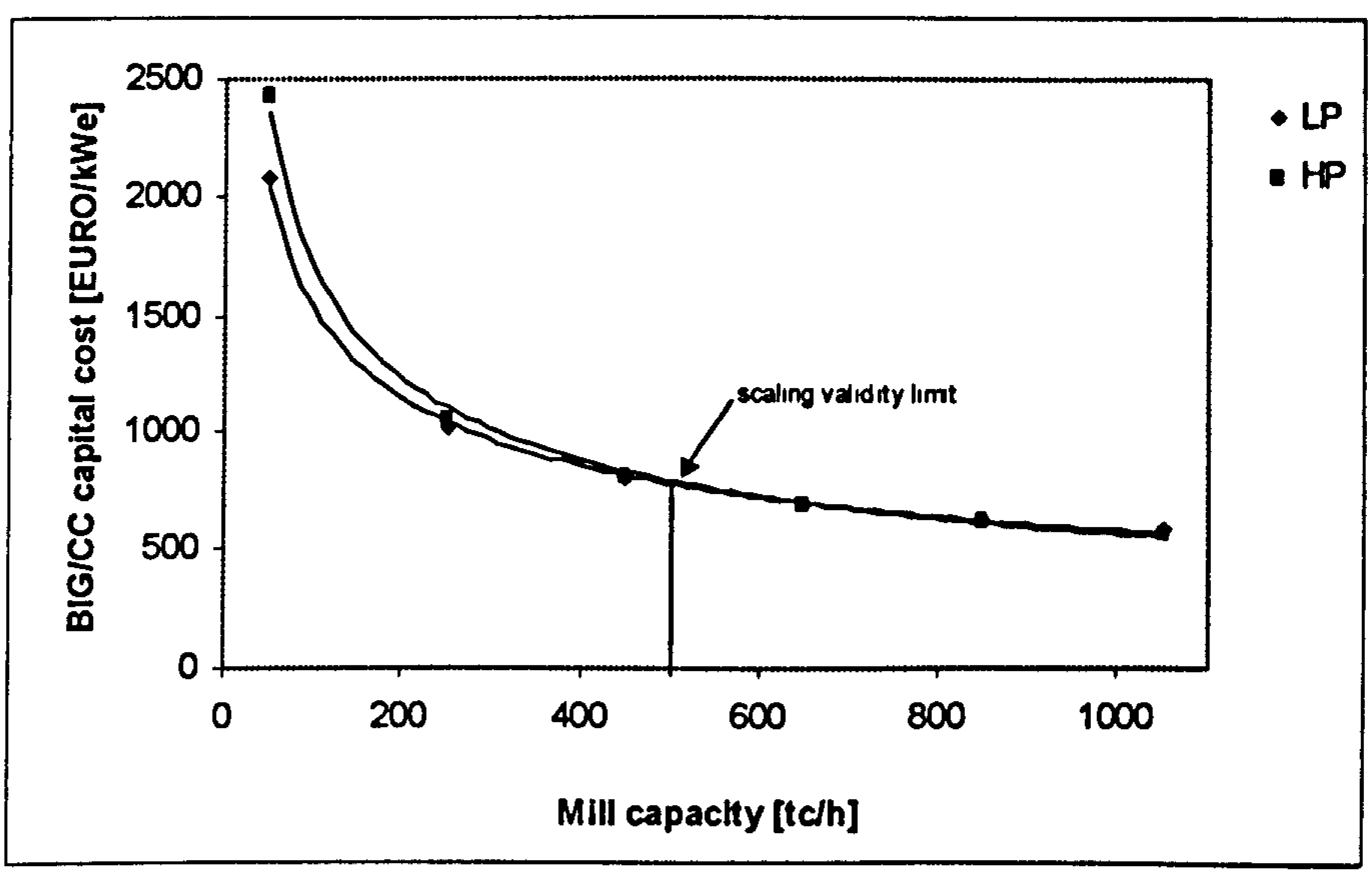

Figure 32: Capital costs for BIG/CC systems installed at cane mills

The validity of the model used for estimating the capital costs of BIG/CC systems of different capacities is judged to be valid for BIG/CC systems of capacities up to about $100MW_e$, which corresponds to the required installed capacity at a mill of about 500 tc/h milling capacity. Beyond this capacity and for mills with milling capacities greater than 500 tc/h, the simplifying assumption that costs remain constant has been made.

Based on the Swedish and UK case studies (see Chapter 5), O&M costs (excluding fuel costs), overheads and contingency have been estimated at about 25% of the plant annualised capital cost.

The bagasse that is not used to fuel the plant during the milling season, estimated to last about 4000 h, is assumed to complement the harvest residues as fuel outside the milling season, up to a maximum of 90% of the initial quantity of bagasse available. The remaining bagasse is assumed to be exported as fuel to other industries or destined to other use (e.g. animal feed). Calculations show that bagasse consumption during the milling season ranges between 67% and 72% of its total for the systems considered and a process steam requirement of 350 kg/tc. The power plant maximum operating time at full load is then calculated to range between 6368 h and 6864 h based on the base case scenario which assumes a 90% recoverability of bagasse and a 25% recoverability of harvest residues as fuel. This represents an overall annual utilisation factor of the BIG/GTCC system of 73% to 78%.

The cost of energy calculations have been performed only for the LP-BIG/CC system, however these are not likely to differ much from those of HP-BIG/CC systems, in particular for the larger scale systems. In a first instance, the cost of electricity has been calculated assuming that all costs are allocated to the production of surplus electricity. The costs calculated range between m€38/kWh$_e$ for a >500 tc/h mill and 5% discount rate and m€145/kWh$_e$ for a 50 tc/h mill and 20% discount rate. Figure 33 and Figure 34 show the cost estimates. Figure 33 shows the cost ranges calculated based on two discount rates (5% and 20%) and indicates the minimum and maximum costs expected. Figure 34 shows mid-range costs calculated for different discount rates (5%, 10%, 15% and 20%).

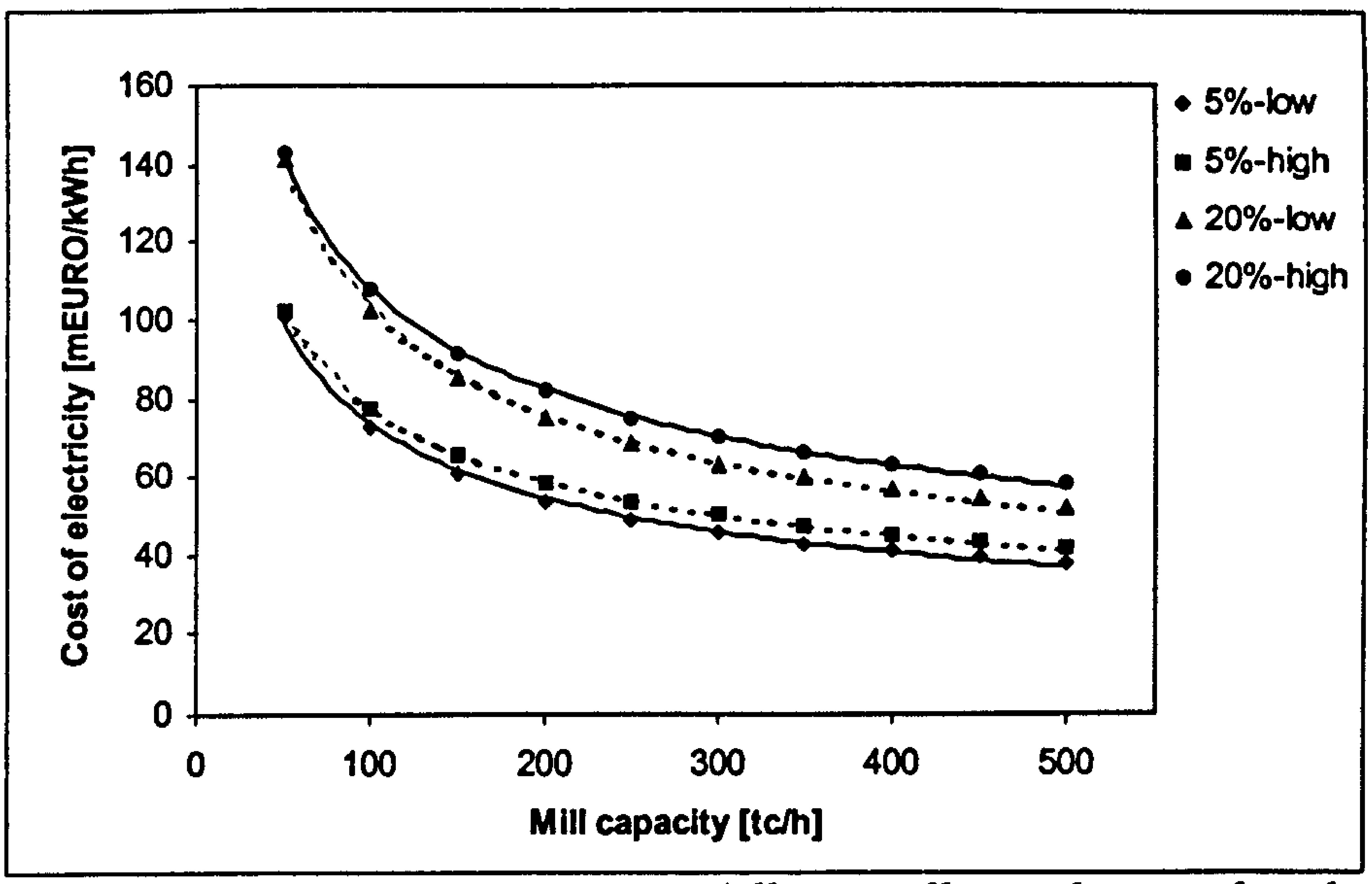

Figure 33: Electricity cost estimate ranges (all costs allocated to surplus electricity)

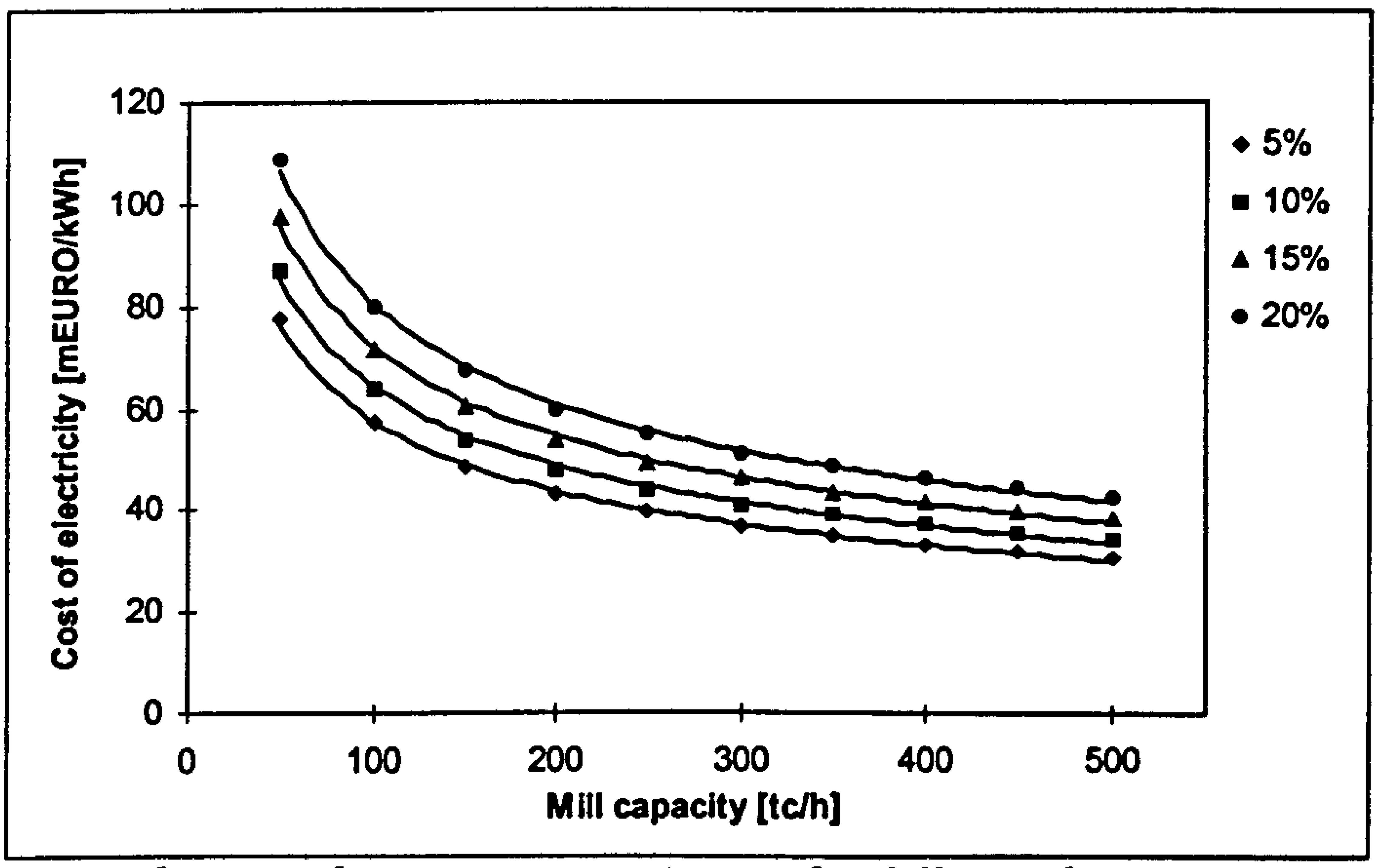

Figure 34: Mid-range electricity cost estimates for different discount rates (all costs allocated to surplus electricity)

Figure 35 and Figure 36 show the cost of electricity based on the system's electricity and useful heat production and allocation of the costs according to the exergy value of the products. An exergy allocation attributes about 72% of the cost to electricity and about 28% of the cost to useful heat. The costs calculated range between m€29/kWh$_e$ for a >500 tc/h mill and 5% discount rate and m€108/kWh$_e$ for a 50 tc/h mill and 20% discount rate.

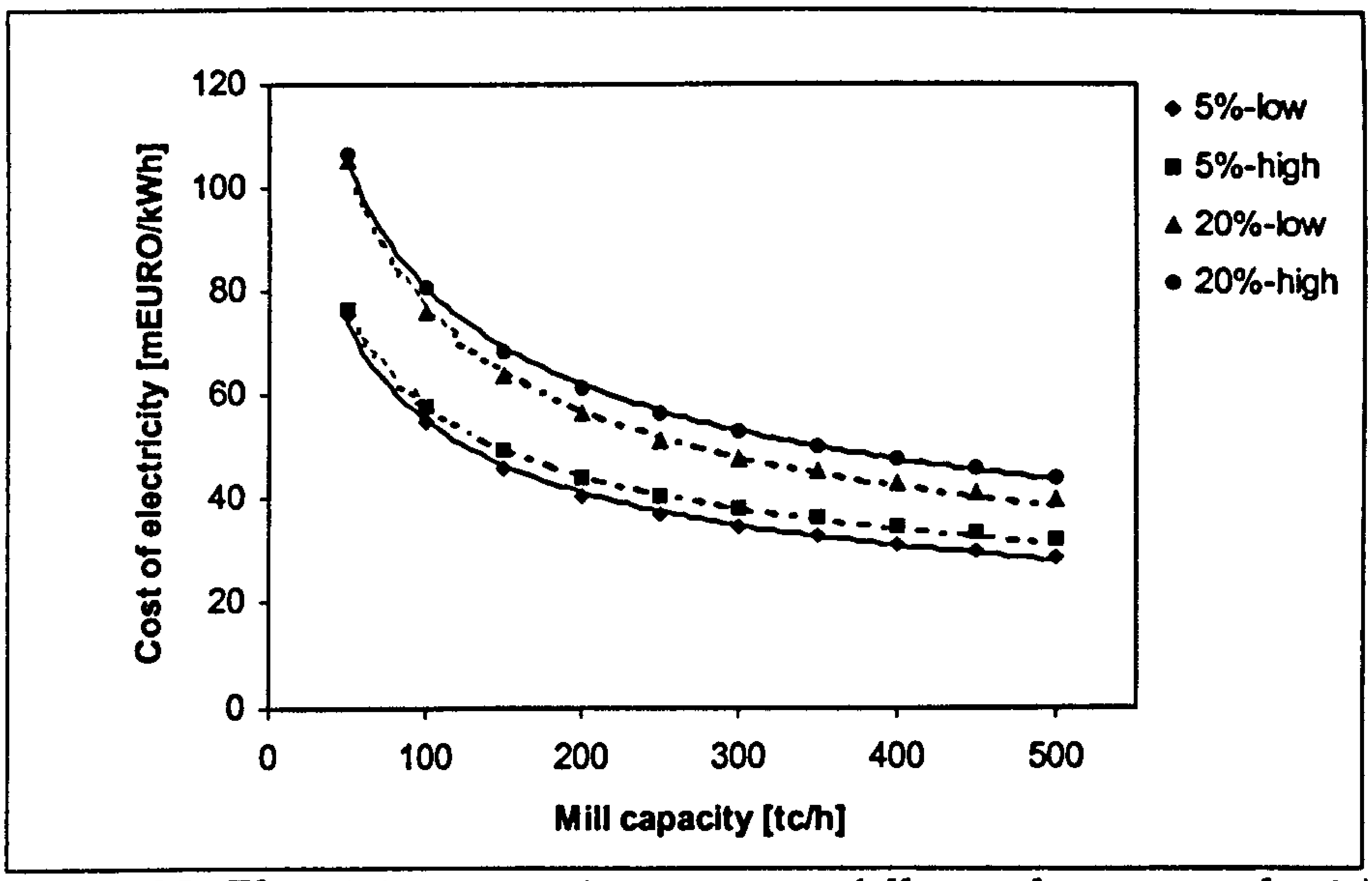

Figure 35: Electricity cost estimate ranges (allocated on exergy basis)

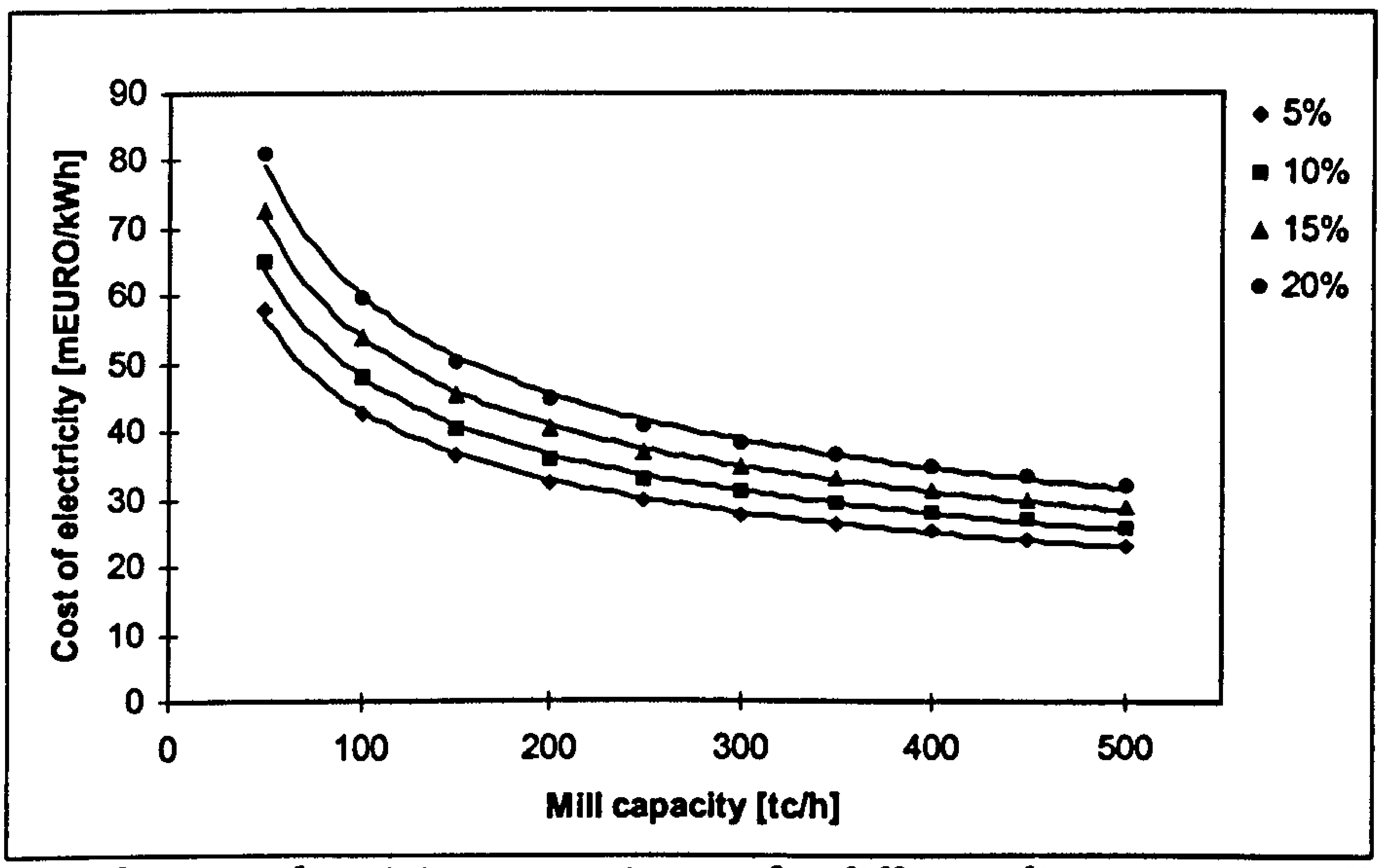

Figure 36: Mid-range electricity cost estimates for different discount rates (allocated on exergy basis)

Similarly, Figure 37 and Figure 38 show the costs of electricity based on the system's electricity and useful heat production and allocation of the costs according to the energy value of the products. The costs calculated range between m€22/kWh$_e$ for a >500 tc/h mill and 5% discount rate and m€76/kWh$_e$ for a 50 tc/h mill and 20% discount rate.

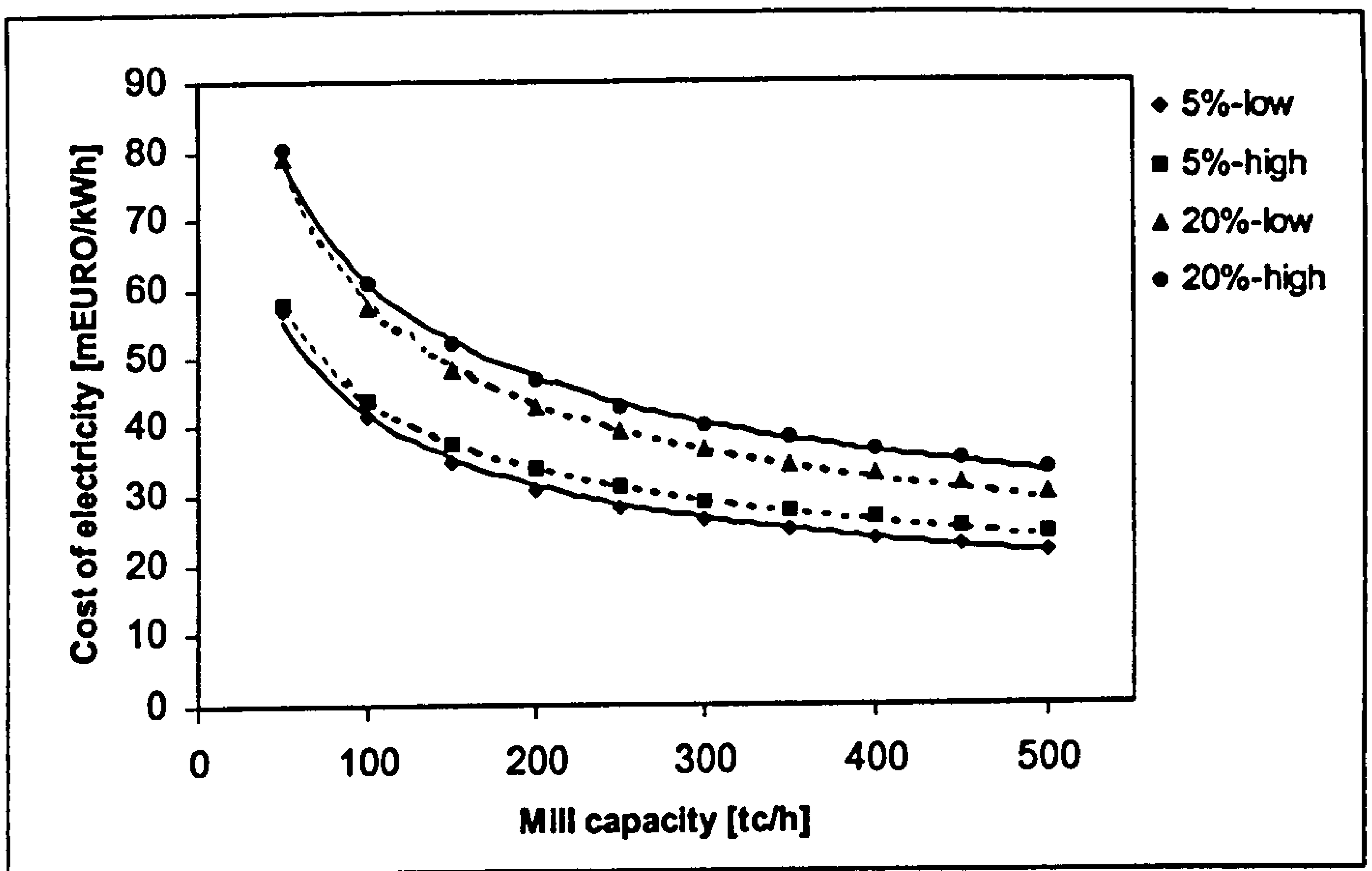

Figure 37: Electricity cost estimate ranges (allocated on energy basis)

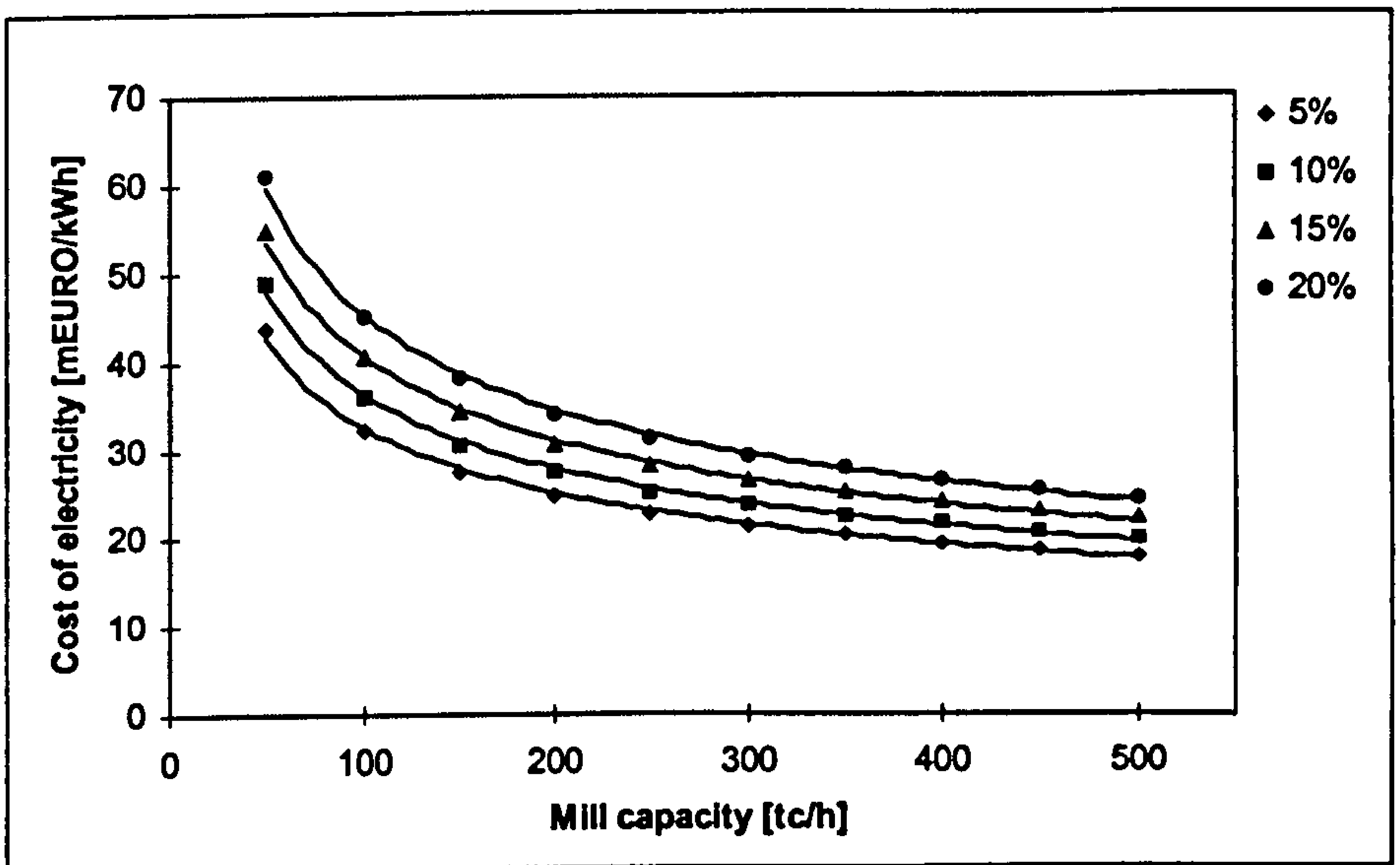

Figure 38: Mid-range electricity cost estimates for different discount rates (allocated on energy basis)

The cost of electricity will vary significantly depending on how the costs are allocated among the electricity and useful heat produced. It is likely that the cost of electricity will lie somewhere between the cost obtained by allocation on an energy basis and the cost obtained by allocating all costs to surplus electricity. Then, for a low discount rate of 5% the cost of electricity will vary between m€22/kWh$_e$ and m€99/kWh$_e$, depending on the installed capacity at the mill site, and for a high discount rate of 20% it will vary between m€30/kWh$_e$ and €145/kWh$_e$. The discount rate is a very influential factor determining the cost of electricity. Using 20% instead of 5% as a discount rate results in a cost increase of over one third.

Figure 39 illustrates the sensitivity of the cost of electricity to four determining paramaters: biomass fuel availability, biomass fuel (harvest residues) cost, investment cost and variable costs other than biomass fuel cost. The calculations have been performed for co-generation at an average size mill of 380 tc/h capacity (e.g. typical of the Usina Ester), which can generate electricity at a cost in the range m€40-44/kWh$_e$ for a 15% discount rate (costs allocated on an exergy basis).

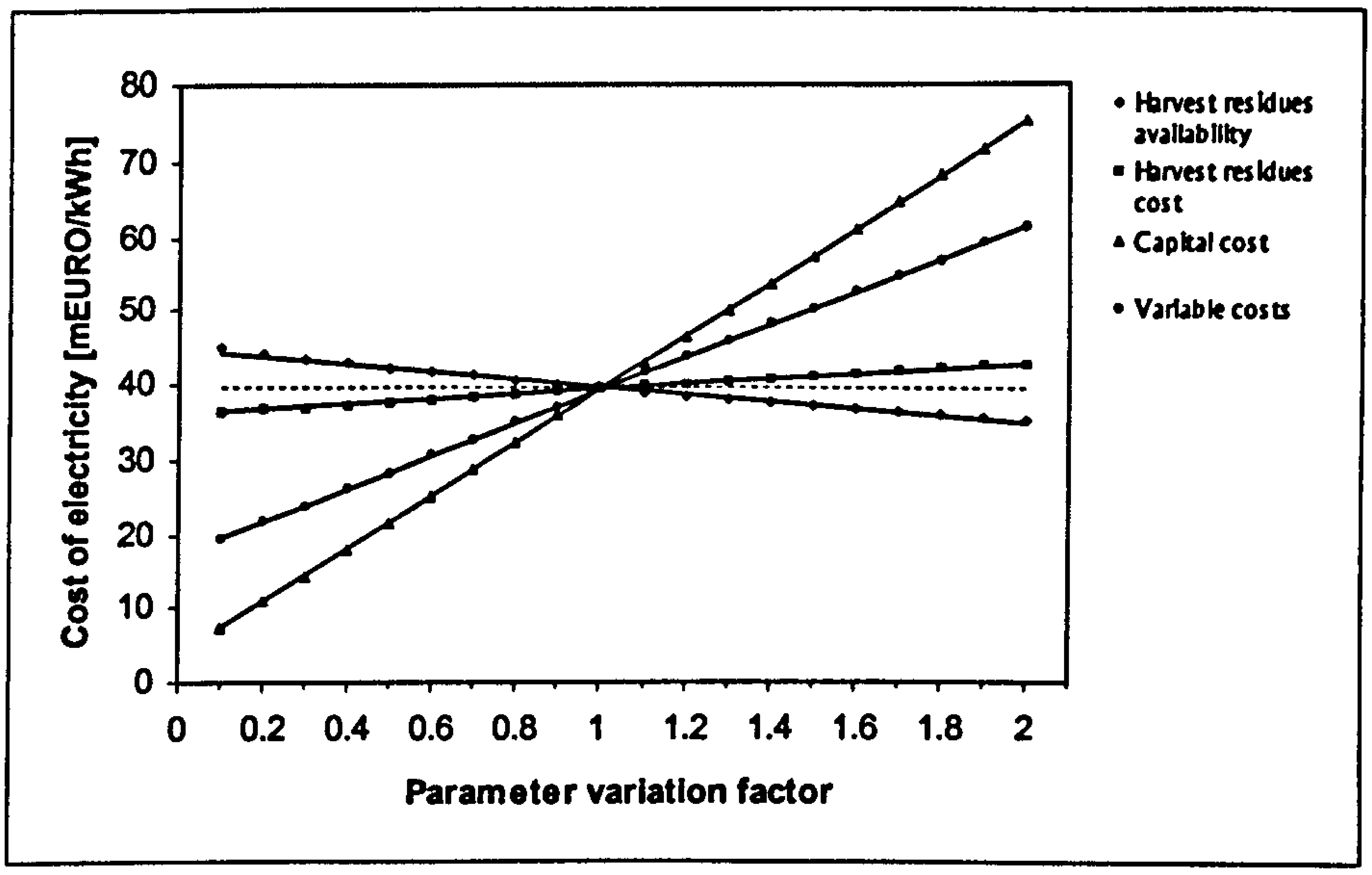

Figure 39: Electricity cost sensitivity

Variations in the co-generation installation capital cost have the greatest influence on the cost of electricity, followed by the variable costs associated with its exploitation (excluding fuel costs). Variations in harvest residues cost are less influential, but of significance. The relatively low influence of harvest residues cost is in part due to the fact that they account for a small fraction of the biomass fuel input to the plant in the base case scenario (the bulk of the fuel being provided by bagasse at an assumed zero cost). Fuel availability (i.e. variations in the amount of fuel available at the same cost) also significantly affects the cost of electricity, by influencing the utilisation factor of the installation. As the sensitivity analysis deals with each parameter independently, it does not emphasise the fact that increasing the contribution of harvest residues to fuel the installation will increase the influence of their cost.

Several estimated projections of marginal costs of electricity supply are found in the literature. ELECTROBRAS (1996) estimates the South/Southeastern Brazil electricity generation expansion marginal cost for a 20 year period at between m€29 and m€34/kWh$_e$ for a 10% discount rate and at about m€46/kWh$_e$ for a 15% discount rate. Coelho and Zylbersztajn (1996) cite estimates of up to about m€54/kWh$_e$, with marginal cost estimates for electricity generation from natural gas and coal of m€37/kWh$_e$ and m€44/kWh$_e$, respectively. Valenzuela Turdera (1997) cites cost of electricity from CCGT estimates between m€27 and m€34/kWh$_e$.

The range of marginal costs for the expansion of electricity generation is quite broad, depending much on assumptions as to the source of electricity and on economic parameters. Nevertheless, the estimated marginal costs are generally significantly higher than the price paid to date for surplus electricity from co-generation in sugarcane processing plants. In 1996, the electricity utilities in São Paulo purchased surplus electricity from the mills at m€8 - m€24/kWh$_e$ (the lower value typical of short-term contracts - 1 year - and the higher value typical of long-term contracts - 10 years) and sold the power to consumers at about m€50/kWh$_e$ (Bajay et al., 1999).

It is difficult to provide a general statement on the likely economic viability of gasification-based co-generation because of the varying costs with mill capacity, the influence of economic assumptions and underlying uncertainties in the exact costs of the systems discussed. Nonetheless, a comparison of the estimates provided above and of the estimated marginal costs of electricity generation from other sources indicates that there is a potential for economically viable gasification-based co-generation at sugarcane processing plants, in particular at medium to large scale plants. Incentives, based on benefits deriving from the decentralised, renewable and clean nature of the systems considered, could enhance their economic competitiveness.

2.4 Direct employment

The fuel cycle activities inventory database and model described in Annex 1 can be used to estimate direct employment for the harvest residues collection and transport activities and for the activities related to the conversion stage. Bagasse production and transport is assumed not to require any labour since it is a waste product generated at the mill site from cane processing activities.

The direct labour input for co-generation from sugarcane bagasse and harvest residues is estimated at 0.43 man h/MWh of biomass fuel used by the fuel cycle. The biomass production stage only accounts for a small fraction of the fuel cycle's labour requirement in the base case. The base case assumption of 25% recovery of harvest residues implies it accounts for 22% of the biomass fuel, the remainder consisting of bagasse assumed not to require any labour up to the conversion stage. Harvest residues collection and transport is estimated to possess a labour requirement of about 0.12 man h/MWh of energy (heat and electricity) produced and the conversion stage is estimated to require 0.4 man h/MWh of energy (heat and electricity) produced.

An enhanced exploitation of the co-generation potential from sugarcane residues will generate employment and, more importantly, should generate full-time employment and improved working conditions compared to traditional jobs in sugarcane production. However, it must be noted that many seasonal jobs will be lost when switching from the manual harvesting of burned cane to the mechanical harvesting of unburned cane.

The indirect effects of the fuel cycle described are likely to be of importance because of the development of indigenous industrial activities producing inputs to the fuel cycle activities.

3 Environmental analysis

The Brazilian sugar and alcohol industry is on average self-sufficient with regard to energy through the use of bagasse. Its use as a fuel has considerable benefits as it is a renewable fuel and it can be considered neutral in terms of CO_2 emissions. Also, bagasse has a negligible sulphur content, which represents an additional advantage compared to most solid and liquid fossil fuels. However, because bagasse is used in relatively old and low efficiency conversion systems, emissions of other conventional pollutants such as NO_x, particulates and CO are likely to be significant and possibly higher than modern conversion systems fuelled with fossil fuels. The externalities per unit of energy generated may therefore be significant for the current use of bagasse.

There is considerable scope to increase power generation within the industry and reduce the externalities per unit of energy generated through the use of the cleaner and more efficient systems proposed (i.e. BIG/CC). In the case of bagasse, the system boundaries have been defined so that no impacts from the sugarcane production cycle are considered, any impacts being associated with the production of sugar and alcohol. In the case of sugarcane harvest residues, the system boundaries include all activities related to their collection and transport, which could lead to significant impacts.

The viability of surplus power exports would be an incentive for the cane industry or third parties to invest in modern, cleaner and more efficient generating equipment. The viability of using harvest residues as a fuel may also accelerate the phase out of the pre-harvest burning of sugarcane fields. Multiple benefits could result from such schemes aimed at generating surplus power for export outside the industry. The externalities of alcohol production would be reduced, and the electricity exported is most likely to present lower externalities compared to electricity from other generating sources.

The environmental analysis will focus on those impacts of the biomass fuel cycle which are judged to have potentially significant effects and have been designated as priority impacts. As discussed in Chapter 6, the biomass production and transport activities considered are limited to the collection and transport of harvest residues.

The quantitative environmental analysis has focused on the atmospheric emissions of the fuel cycle, in particular on the emissions which could lead to significant impacts. The collection and transport of residues are likely to make a significant contribution to the fuel cycle's emissions. However, the most significant impacts are likely to result from the atmospheric emissions of the conversion stage. Collection and transport will contribute some net CO_2 emissions to the fuel cycle, while no net emissions are attributed to the conversion stage because all C emitted is assumed to have been previously captured from the atmosphere in the sugarcane growth phase. Atmospheric emissions are also considered to result in the impacts of greatest significance in the case of the reference fossil fuel cycles (CEC, 1995). The biomass and reference fuel cycles will then be mainly compared on the basis of atmospheric emissions.

Other impacts, in particular on soil quality due to the removal of residues and the use of machinery, have been qualitatively discussed and are not likely to be significant if good agricultural practice is followed (see Section 7 of Chapter 6).

The lack of data necessary for the quantification of environmental impacts for Brazil does not allow for a calculation of the impacts and externalities. An indicative quantification and discussion of the impacts and externalities based on the results of externalities assessments carried out for Europe will be addressed in Chapter 8.

3.1 Atmospheric emissions analysis

This section provides and discusses estimates of the atmospheric emissions of the biomass and reference fuel cycles. Only direct emissions estimates are provided for the Brazilian case study, but indirect emissions, as in the case of the Swedish and UK case studies, are likely to be of little significance.

As discussed in Chapter 2, it is meaningful to compare emissions for different systems which generate the same quantity of desired end-products (i.e. heat and electricity). In which case it has been decided to compare a mill-based BIG/CC system generating surplus electricity to a system consisting of CCGT for electricity only generation and some form of co-generation which would satisfy the heat and electricity demand of the mills. This study is principally concerned with the potential for surplus electricity generation from sugarcane residues (bagasse and harvest residues) for input to the electricity grid, and emissions allocated to the surplus electricity production are then compared to electricity generated from a CCGT-based fuel cycle.

However, for a complete comparison, the emissions attributed to the generation of heat and electricity to satisfy the mills' energy demand through the BIG/GTCC system would have to be compared to those of an alternative system supplying the mills' energy needs. Although the total (heat and electricity) energy efficiency of an alternative system, of the type which would be used only to satisfy the mills' energy needs (i.e. based on boilers and steam turbines), may be similar to that of a BIG/CC system, its emissions per unit of energy generated are likely to be higher. To base the comparison uniquely on the emissions attributed to the surplus electricity, would therefore ignore the additional benefits of using BIG/CC to satisfy the mill's energy needs.

Table 44 provides estimates of the emissions occurring at each stage of the sugarcane residues fuel cycle obtained from detailed fuel cycle inventory calculations (Annex 1). Emissions from the biomass production and transport stages of the fuel cycle refer to the harvest residues collection and transport activities. The emissions estimates for the conversion stage are for LP-BIG/GTCC systems based on information from demonstration projects and from equipment manufacturers, and on the composition of sugarcane residues. The table also contains the emissions for the reference fuel cycle. Aggregate emissions are provided for the extraction, transport and processing stages of the CCGT fuel cycle, and it is assumed that the combustion co-generation system is fuelled with bagasse, which assumes no activities associated with biomass fuel production and transport. Separate emissions are provided for the point source emissions from the conversion stage (see Section 7 of Chapter 4) and these consist of a weighted average of the emissions based on the energy produced by the combustion co-generation and CCGT sub-systems. The last column in the table shows the total fuel cycle emissions. Figure 40 compares the emissions from the biomass and reference fuel cycles.

Table 44: Emissions per unit of energy (heat and electricity) generated by 'system 1' and 'system 2' (all emissions in mg/kWh except CO_2 emissions which are in g/kWh)

	Production	Transport	Conversion	Total
NO_x 'system 1'	10.83	2.16	128.29	141.29
NO_x 'system 2'	21.10		478.16	499.25
SO_2 'system 1'	0.23	0.05	3.36	3.63
SO_2 'system 2'	9.09		1.58	10.67
PM 'system 1'	1.63	0.25	7.15	9.03
PM 'system 2'	0.86		9.74	10.60
CO 'system 1'	4.36	0.75	335.03	340.14
CO 'system 2'	7.46		226.54	234.00
NMHC 'system 1'	2.00	0.23	0.00	2.23
NMHC 'system 2'	7.32		17.98	25.30
CO_2 'system 1'	0.69	0.14	0.00	0.83
CO_2 'system 2'	5.53		208.22	213.75

System 1: LP-BIG/CC system fuelled with bagasse and harvest residues
System 2: Biomass combustion system fuelled with bagasse to supply mill's energy needs and CCGT to supply additional electricity to match surplus electricity from system 1

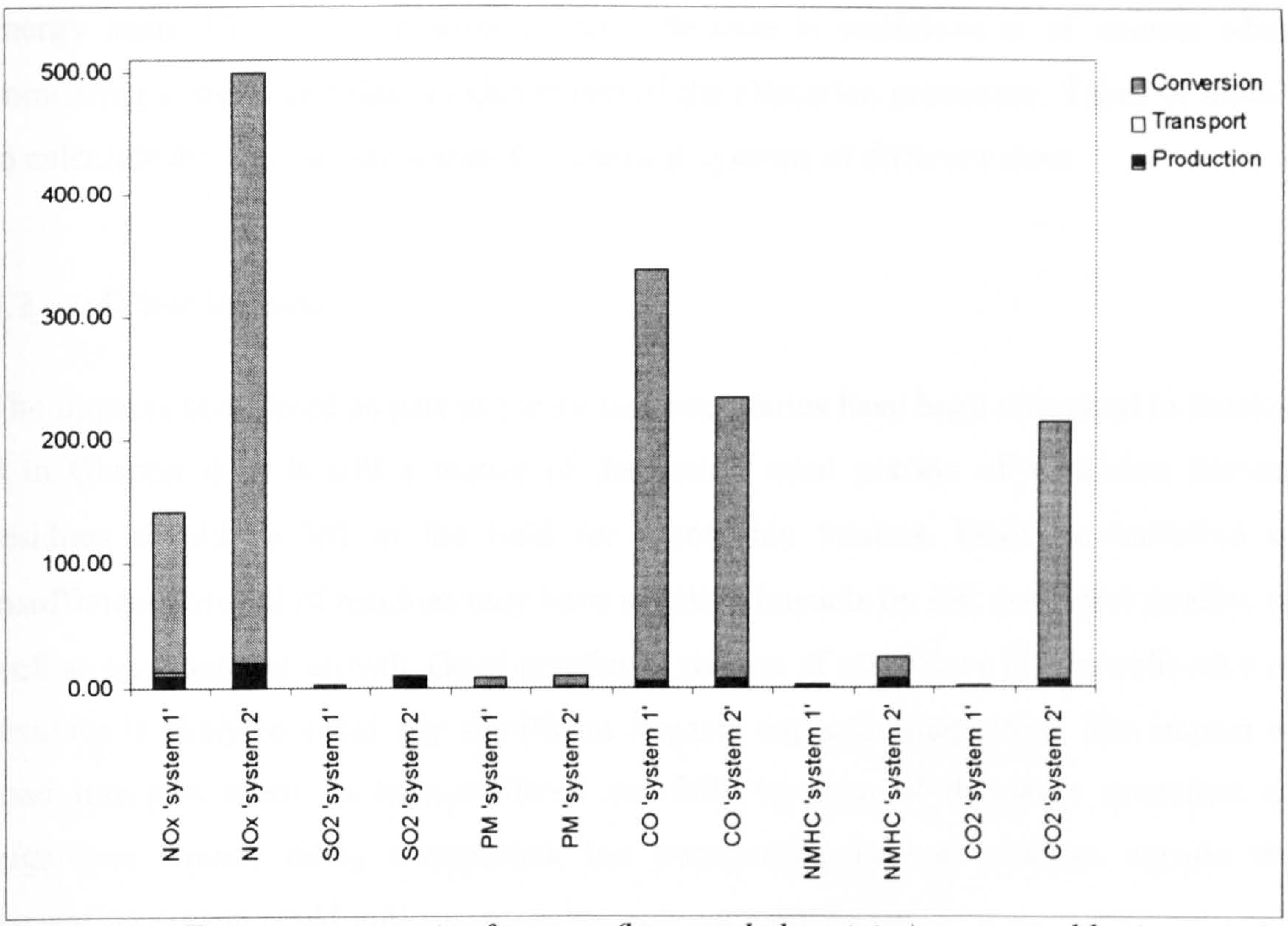

Figure 40: Emissions per unit of energy (heat and electricity) generated by 'system 1' and 'system 2' (all emissions in mg/kWh except CO_2 emissions which are in g/kWh)

Emissions from the fuel production and transport stages represent dispersed emissions as opposed to emissions from the stack which are considered as point source. However, most direct emissions from the biomass fuel cycle are likely to occur in the vicinity of the plant. The distinction between dispersed and point source emissions is of no relevance with regard to greenhouse gas emissions due to their global effect.

The gasification-based co-generation system appears to possess advantages for all emissions except CO. In particular, substantial benefits may arise from the significant reduction in NO_x and CO_2 emissions. The above comparison is based on mid-range emission values for the systems considered. For certain emissions from the conversion stage a range of values is available and Table 79 and Table 80 in Annex 1 provide an indication of the extent of these ranges. The emissions from the gasification-based system have been discussed in detail in Section 7.1 in Chapter 5.

It is important to note that the relative difference in emissions will depend much on the type of allocation. For example, an allocation on an exergy basis will attribute greater weight to the emissions associated with electricity generation, and in our specific reference case to the emissions from the CCGT plant, compared to an allocation on an energy basis. However, the absolute net difference in emissions is of interest when comparing systems and this is independent of the allocation procedure. Table 44 allows to calculate the absolute emissions for identical systems of different sizes.

3.2 Other impacts

The impacts considered as part of the system boundaries have been discussed in Section 7 in Chapter 6. It is still a matter of discussion what portion of sugarcane harvest residues should be left in the field for agronomic reasons. Both an excessive or insufficient removal of residues may have negative impacts on soil and water quality, as well as on sugarcane growth. Good practice in the use of machinery for the collection of residues is likely to avoid any significant impacts e.g. soil compacting. The impact of road transport needs to be considered carefully because of the large quantities of sugarcane already being transported, but transporting harvest residues outside the harvesting season could mitigate some impacts e.g. congestion.

4 Energy analysis

The energy balance for gasification-based co-generation using sugarcane residues is very favourable. This is due to the fact that harvest residues and bagasse are renewable fuels, and that a large part of the fuel, in the form of bagasse, is produced at the mill site, assumed to require no energy inputs for its production and transport.

For a gasification-based co-generation plant installed at an average Brazilian mill, the non-renewable energy requirement is estimated at 0.037MJ/MJ biomass fuel input to the plant and at 0.053MJ/MJ of energy generated, the latter corresponding to an energy ratio of about 19. The non-renewable energy input consists of fossil fuel consumption for the collection and transport of harvest residues, energy embodied in materials (e.g. twine and synthetic cover) and machinery, and the energy requirement of plant construction (see section 5 of Chapter 5 and Annex 1).

For the reference system, the energy requirement of a natural gas CCGT fuel cycle is estimated to be 2.34MJ/MJ of energy (electricity) generated (corresponding to an energy ratio of about 0.43) and the energy requirement of a combustion-based co-generation fuel cycle using bagasse is estimated to be 0.065MJ/MJ of energy generated (corresponding to an energy ratio of about 15). The average energy ratio for the reference system is then estimated at about 7 by using the energy shares in Table 43 of Section 8 in Chapter 6. It goes without saying that enormous savings in fossil fuel consumption would arise if surplus electricity from the sugar and alcohol industry were to be used in place of electricity from natural gas or other fossil fuels. The energy balance for sugarcane residues based co-generation is likely also to be more favourable compared to the energy ratio of large hydroelectric schemes, estimated at about 11 in Mortimer (1991).

5 Conclusions

This chapter has provided an economic, environmental and non-renewable resource use assessment of BIG/CC systems fuelled with sugarcane residues compared to reference systems. The short-term economic viability of gasification systems remains an issue although the results of the analysis indicate that they may be economically viable for installed capacities at medium to large-scale mills. The environmental and resource use advantages of BIG/CC systems are more evident, and their translation into economic benefits could contribute to the systems' viability.

Sugarcane residues can provide a relatively low cost biomass fuel. The cost of harvest residues delivered to the plant is estimated to range between €1.22 and €1.73/GJ. Materials used in the baling of the harvest residues (i.e. twine) and to cover the bales during storage (i.e. synthetic cover) account for a significant portion of the cost, 25% and 19%, respectively, in the case of an average sized mill (300 tc/h). Transport costs are found to represent between 9% and 17% of the cost depending on mill size. The cost range is believed to be suitable for economically viable biomass energy systems, and cost reductions could possibly be achieved. Bagasse can be considered as being available at zero cost or as having a low opportunity cost.

Bagasse utilisation during the milling season (c. 4000 h) is estimated at 67 – 73% of its total for a processing plant with a process steam requirement of 350 kg/tc. Base case assumptions on the availability of bagasse and harvest residues extend the annual operation of the generating facility to between 6368 and 6864 h, corresponding to an annual utilisation factor of 73 – 78%.

The cost of energy expectedly varies widely depending on the installed capacity and discount rate. For a 5% discount rate the cost of electricity is estimated to range between m€22 and m€99/kWh$_e$, and for a 20% discount rate it is estimated to range between m€30 and m€140/kWh$_e$. The way costs are allocated to the different energy vectors (i.e. heat and electricity) also affects the cost of electricity. Investment costs, variable costs (excluding fuel cost), fuel availability and fuel cost are, in order, the most significant factors affecting the cost of energy for a given installed capacity. The costs estimated indicate that there is a potential for economically viable gasification-based co-generation at sugarcane processing plants, in particular for medium to large-scale plants.

The prospect of a potential use of the large quantities of residues, which would arise from the harvesting of unburned cane, may accelerate the transition from manual harvesting of burned cane to mechanical harvesting of unburned cane. Efficient mechanical harvesting is also likely to reduce harvesting costs, and the halting of the burning of sugarcane fields prior to harvest will result in an obvious environmental benefits. However, as a consequence many jobs would be lost during the harvesting season. This is definitely an issue which needs to be addressed in envisaging a transition to mechanical harvesting.

The use of harvest residues as a fuel will require labour and can contribute somewhat to mitigating the loss of manual harvesting jobs resulting from an increased mechanisation of sugarcane harvesting. Furthermore, the jobs generated are likely to be more stable and to offer improved working conditions.

Gasification-based co-generation fuelled with sugarcane residues and producing surplus electricity for export to the grid can lead to significant reductions in emissions compared to reference energy systems. It appears to possess advantages for all emissions except CO. In particular, substantial benefits may arise from the significant reduction in NO_x and CO_2 emissions. A more detailed quantification of the environmental benefits is attempted in Chapter 8.

The use of sugarcane residues for the production of surplus electricity can lead to large savings in fossil fuel consumption, strongly reduce future non-renewable energy requirements, if the electricity generated replaces electricity from natural gas or other fossil fuels. The energy ratio for sugarcane residues based co-generation is likely also to be more favourable compared to the energy ratio of large hydroelectric schemes. Consequently, the indigenous nature of the biomass fuel can contribute positively to the national balance of payments, as opposed to imported fossil fuels.

CHAPTER 8

BIOMASS FUEL CYCLE EXTERNALITIES AND SUSTAINABILITY

1 Introduction

Decision making processes will consider private costs and benefits, whilst often ignoring a series of additional costs and benefits, known as externalities, which are then borne by society as a whole. A blatant example of externality is the damage caused by pollution. Policies can be adopted to internalise the externalities. Also, accounting for the full costs of economic activities is one possible step towards strategies aimed at sustainable development.

Energy generation and its use in the residential, commercial, industrial and transport sectors has severe consequences on the local, regional and global environment. Smog, acidification and climate change are some of the environmental concerns associated with energy related activities, and to these we can add concerns regarding resource depletion, energy security and the drain on the economic resources of countries poor in primary energy sources. All these and more may translate to external costs which are generally not accounted for when choosing amongst different energy supply and end-use options.

Chapter 2 introduced the concept of externality, discussed methodological approaches for their evaluation, the importance of their internalisation and their limitations. The ExternE methodology, used in this study for the assessment of externalities from atmospheric emissions, has also been described. This chapter begins with a discussion on the state-of- the-art of energy externalities, followed by a discussion of biomass fuel cycle externalities with particular emphasis on the Swedish, UK and Brazilian case studies discussed in the previous chapters. The chapter closes with a discussion on the total costs and benefits and on the sustainability of the biomass fuel cycles and their role in the future of sustainable energy.

2 Review of the externalities of energy

A number of studies have addressed the externalities of energy, and Table 45 provides ranges for the externalities of different fuel cycles obtained by some prominent studies since the late 1980s. The review which follows provides an indication of the impacts on which valuation has focused to date, the magnitude of energy externalities, the differences in values between studies and the relative importance of different impacts.

Studies have mainly focused on the impacts of fuel cycles on human health, and these generally represent the most significant contribution to the value of the externality. In cases where estimates of damage from climate change caused by the emission of greenhouse gases are considered, they often overwhelm other externality values. The range of externality values is also wider where damages from climate change are considered because of even larger uncertainties compared to other impacts. Apart from the uncertainties surrounding the physical impacts of climate change, further uncertainty is added by different economic assumptions made in valuing potential damages. Typically, the level of discounting is the cause of considerable controversy and an important ethical issue. Small changes in the discount rate cause large variations in damage estimates because of the long-term effects of climate change.

Table 45: Review of externalities of energy [m€/kWh]

	Hohmeyer (1988)	**Friedrich and Voss (1993)**	**Ottinger et al. (1990)**	**RCG/ Tellus (1995)**	**Masuhr and Ott (1994)**	**ORNL/ RFF (1994)**	**Pearce (1995)**	**CEC (1998a)**
Coal	31 - 71	3.0 - 15	22 - 51 (13)	2.3	-	0.5 - 0.8	11 - 62 (5.4 - 6.1)	6.1 - 240 (3.8 - 137)
Oil	-	-	22 – 52 (9.2)	1.5	46 - 673 (24 - 653)	0.2	44 - 70 (5.4)	15 - 190 (3.0 - 121)
Gas	-	-	6.1 - 9.2 (6.0)	0.15	25 - 466 (17 - 457)	0.008 - 0.2	4.6 - 5.4 (2.3)	2.3 - 80 (1.5 - 75)
Nuclear	78 - 167	0.2 - 4.6	26	0.08	2.3 - 23 (0.8 - 21)	0.15 - 0.23	0.5 - 3.8 (0.2)	2.3 - 7.6 (0.08 - 0.3)
Biomass	-	-	0 – 6.1	2.3	-	1.4	3.0 (0.3)	0.8 - 32 (0.6 - 2.3)
Hydro	-	-	-	-	1.5 - 9.2	0 - 0.2	0.5 (0.06)	7.6 - 6.9
Solar	*55 - 138*	0.4 - 9.2	0 - 3.8	-	-	-	0.8 (0.04)	0.6 - 8.4 (0.2 - 7.6)
Wind	*45 - 99*	0.2 - 3.0	0 - 0.8	0.008	-	-	0.2 - 0.5 (0.04)	0.4 - 3.8

Note: values in parentheses indicate contribution of climate change externality to the externality value provided, italics denote an environmental benefit.

Hohmeyer (1988) uses a top-down approach to value damages associated with environmental impacts of fossil fuel generation on flora, fauna, humans and materials, and considers climate change impacts. A single externality has been attributed to electricity from fossil fuels in general, expressed per unit of electricity generated. However this cost is likely in most part to be attributable to coal, in particular old coal plants, which should account for most of the damage. The external costs of nuclear energy are found to be large and are attributed to impacts on human health from normal operation and accidents and to resource depletion. Climate change accounts for just a small part of the externalities valued in this study, representing less than 1% of the estimate.

The study also considers a number of non-environmental externalities such as the depletion of non-renewable resources and government subsidies, with the first contributing between a quarter and half of the externality estimate for fossil fuels and between one third and two thirds of the value for nuclear. The externalities estimated are believed to represent only the tip of the iceberg and consideration of further externalities would further strengthen the stance of renewables. The net benefits of wind and solar energy result from economic effects such as gross value added, savings and employment.

Hohmeyer's study being one of the first studies to attempt the quantification of the externalities of energy attracted great attention, in particular because it indicated that the externalities of conventional generation are significant and similar in magnitude to the price of electricity. As a response, Friedrich and Voss (1993) carried out a similar study which resulted in much lower externalities for fossil and nuclear fuel cycles. The study rejects most of the non-environmental externalities claimed by Hohmeyer (1988) (e.g. employment), estimates the cost of utilisation of non-renewable resources as being small and possibly internalised, and estimates R&D expenditure and public subsidies as being significant externalities. R&D expenditure account for most of the externality estimate in the case of wind and solar.

Certain institutionalised subsidies to specific sectors, which are not aimed at correcting market imperfections may be seen as externalities. The elimination of subsidies, apart from those aimed at internalising external costs, is desirable to achieve a level playing field where energy sources can compete. For those technologies for which cost reductions could realistically be achieved that will allow them to compete in terms of social costs, RD&D support is necessary because of market imperfections not allowing it by private enterprise, and it should not be considered as an externality. It is rather an investment on the part of society to reduce future social costs.

The PACE study (Ottinger et al. 1990) is based on a literature review of environmental impacts based on bottom-up studies. The externalities valued refer to damages of air pollution. The damage cost of climate change impacts accounts for a large portion of the externality associated with the fossil fuel cycles. The bulk (80%) of the externality of the nuclear cycle is associated with the risk of accidental emissions. The externalities associated with renewable energy are mainly a result of toxic emissions from the manufacturing process in the case of photovoltaics, of noise in the case of wind and of atmospheric emissions in the case of biomass.

Masuhr and Ott (1994) and Ott (1996) discuss a top-down approach applied to Switzerland. The externalities of the fossil fuel cycles account for the damages of air pollution to human health, buildings, agriculture and forestry. The nuclear energy externality accounts only for estimated deaths caused by normal plant operation. The principal externalities associated with hydropower are a result of the impairment of natural landscapes and the impacts on water systems. The externality values are based on willingness to pay surveys on conservation and biodiversity and on the valuation of the recreational function of natural landscapes. The costs of climate change are valued in terms of damage cost estimate ranges and average avoidance costs for Switzerland (damage cost estimates are shown in Table 45).

Pearce (1995) estimates externality adders for UK power generation based on a literature review of externalities associated with different pollutants and on a range of emissions for different generating technologies. The estimates account for air pollution and climate change impacts. The damage cost associated with climate change is based on a value estimated by Fankhauser (1995). The externality adder for nuclear energy is largely a result of damage estimates for accidental emissions. The externality estimates for hydro and wind only account for damages from emissions of pollutants from equipment production and from the construction stage, and do not include, although they are mentioned, more site-specific effects such as noise, landscape changes and effects on fauna, which may be dominant for such generating systems.

The RCG/Tellus (1995) study, also known as the New York State Externalities Study, is based on a bottom-up approach. The study considers the impacts of air, water and soil pollution. For fossil fuel cycles, air pollution impacts are the only ones of significance. The study does not account for climate change impacts. Impacts of water pollution appear to be significant in the particular biomass case considered. The nuclear energy externalities are dominated by radiation exposure impacts from normal operation. The wind energy externalities are a result of impacts on the landscape. The externality adders calculated are lower than those obtained by the previous studies. However, the results for the Sterling, NY, site are particularly low, and within the same study, the siting of fossil facilities (natural gas and oil) at other sites has resulted in increases in externality adders of up to a factor of eight. Ottinger (1996) has criticised the study as suffering from serious omissions and undervaluations and suggests corrected values for the coal atmospheric fluidised bed combustion (AFBC) case. The RCG/Tellus damage costs for the AFBC plant range between €0.2/MWh and €2.4/MWh, and the range provided by Ottinger is between €0.7/MWh and €15.4/MWh (between €19.9/MWh and €34.5/MWh including climate change damage estimate). Ottinger's criticism extends to other bottom-up studies.

The most recent and extensive effort to value the externalities of energy is provided by the ExternE project. The third phase of the project (CEC, 1998a) has assessed the externalities of fossil, nuclear and renewable fuel cycles across the European Union member states. For the fossil fuel cycles the range of externalities is strongly influenced by the technology chosen for the case studies and by their location. For example, a similar facility sited in Sweden and in Germany is likely to present lower externality values for Sweden because of the likely lower population which may be exposed to pollution. Such site-specific effects may lead to different priorities with regard to the impacts of fuel cycles at different sites. In the case of the nuclear fuel cycle, the external costs associated with the risk of accidental emissions are very small. However, the study admits that much controversy exists on how public perception of risk should be included in the analysis. Most of the damages are attributed to radioactive emissions of abandoned mill tailings and to climate change impacts of the emissions from reprocessing stages. The externalities of the biomass fuel cycles are generally lower than those of the best fossil fuel cycle considered. The external benefit obtained for hydropower reflects the Austrian case study where only benefits of protection from flooding and effects on navigation have been considered. The site dependency of externality estimates is also likely to be great for hydropower because of the strong influence of local amenity and ecological issues. The externalities of both nuclear and renewables are small, but the uncertainties over the risks associated with nuclear are much larger.

The recent BioCosts study (CEC, 1998b) has focused on the externalities of biomass fuel cycles and their comparison to reference fuel cycles at different sites within the European Union. The study is based on the ExternE methodology and the results of the externalities calculations carried out for Sweden and the UK in the present work are part of it. The ranges of externalities for the case studies other than those discussed in detail in this study are provided in Table 46 and are discussed in more detail in Section 3.1.

Table 46: BioCosts study results [m€/kWh] (CEC, 1998b)

	Biomass				Fossil			
	Original site		Lauffen DE		Original site		Lauffen DE	
	Conversion	All stages	Conversion	All stages	Conversion	All stages	Conversion	All stages
Nässjö SE[1]	0.8	1.1	3.9	5.1	3.5	4.6	15	20
Mangualde PT[2]	8.7	8.9	15	16	110	110	180	180
Hashoj DK[3]	6.9	8.1	19	23	6.3	6.3	18	18
Weissenburg DE[4]	140	140	150	160	150	160	180	180

[1] Utilisation of forestry residues in the Nassjo circulating fluidised bed combustion plant, Sweden, versus the use of Polish coal in the same plant.
[2] Utilisation of woody biomass for industrial combined heat and power production in Mangualde, Portugal, versus the use of fuel oil in an engine generating heat and power.
[3] Production of biogas from slurry for municipal combined heat and power generation at Hashöj, Denmark, versus the use of Danish natural gas in the same engine.
[4] Production of cold-pressed rape-seed oil and its use in a co-generation plant at Weissenburg, Germany, versus the use of diesel fuel in a similar engine.

Few studies on the externalities of energy have been carried out outside Europe and the US. A study by Carnevali and Suarez (1993) assessed the effects of Argentinean energy policies of the 1970s and 1980s on air pollution emissions and emissions control costs. It is estimated that fuel switches avoided a capital expenditure on emissions control of over $1.5 billion. Van Horen (1996) carried out an assessment of the externalities of coal and nuclear energy for South Africa. The externalities of coal consider mining injuries and deaths, health impacts from air pollution and climate change impacts, and they range between m€4.6 and 26/kWh (m€1.2 and 1.8/kWh excluding climate change impacts). The externalities for nuclear consider exclusively fiscal subsidies and range between m€6.7 and 24/kWh. Furtado (1996) carried out a contingent valuation study to assess the WTP to avoid environmental impacts from hydro, coal and nuclear power in Brazil (Table 47). The study which related to three specific facilities showed public preferences to favour hydropower, followed by coal and finally nuclear. After comparison with externalities determined in other European and US studies, Furtado found the values to be sufficiently reliable for use in cost-benefit analysis of energy generation options. However, for the facilities considered, the inclusion of the external costs considered would not have influenced their ranking based on private costs. Furtado's study is a pioneer in the valuation of energy externalities in Brazil. The study though relies on contingent valuation alone, with all impacts aggregated in a unique value, and lacks specificity with regard to technology and knowledge of actual impacts.

Table 47: CVM estimates of externalities of energy in Brazil (Furtado, 1996)

Conversion facility	Externality [m€/kWh]
Hydro	2.9 - 6.2
Coal	10 - 21
Nuclear	23 - 45

A discussion on the limitations of externalities has been provided in Chapter 2. The review of the externalities of energy illustrates the wide range of values found in the literature. The assumptions and methods vary greatly for the different studies, and many results are strongly site dependent. However, it can generally be concluded that the externalities of energy are most likely to be significant in relation to the current price of energy. The difference in externality between fossil and renewable sources is also likely to be significant, in particular when considering CO_2 emissions. Greatest benefits of renewables appear when comparing old coal technology to wind, while the benefits are reduced when comparing natural gas to biomass, where the benefit may largely be attributed to reduced CO_2 emissions. The case of natural gas and biomass fuel cycles will be discussed in greater detail in the following sections. The range of externalities of nuclear energy is large, mainly due to difficulties in assessing the risk of nuclear accidents. But, nuclear energy also presents difficulties (e.g. disposal of radioactive waste material) which are likely to influence significantly the fuel cycle private costs and pose questions on the sustainability of the fuel cycle.

3 The externalities of biomass energy

The social cost of biomass energy needs to be considered in comparison to that of energy from other sources for future energy sector decision and policy making in the quest for more sustainable energy systems.

A biomass fuel cycle for power generation, like a fossil fuel cycle, consists of fuel production, transportation and conversion stages and a waste disposal and recycling stage. There are though some fundamental differences in terms of impacts and their distribution. The burdens of fuel production and fuel conversion usually arise at different and distant locations in the case of fossil fuels, but are generally close for biomass fuel cycles. In the case of fossil fuel cycles, the impacts from the fuel production stage are considered as having little significance compared to the impacts from the generation stage, and externalities estimates have focused on the damages of emissions to air from the conversion stage. It is most likely though that the focus on the conversion stage has tended to underestimate the externalities of upstream activities. In the case of biomass, fuel production activities generally play a more significant role. In particular, when biomass fuel cycles make use of purpose grown energy crops, the effects of their production may be diverse and significant. Also, impacts from the transport of biomass fuels, solid fuels in particular, may be significant because of the relatively low density of the fuel and the fact that transport is often carried out by road. The type of conversion technology, as in the case of fossil fuels, is a key factor influencing the impacts of the fuel cycle and the relative importance of the different stages. The conversion of biomass is generally considered neutral in terms of CO_2 emissions, and biomass fuel cycle CO_2 emissions result essentially from the production and transport stages. Impacts from waste disposal and recycling are generally not likely to be significant. The potential impacts and priority impacts for the fuel cycles considered in this study have been discussed in the previous chapters.

3.1 Recent studies on the externalities of biomass energy

There has been a steady evolution in the attention dedicated to the externalities of biomass energy since the late 1980s. Past studies provide an insight into externalities of biomass fuel cycles which may prove useful when addressing the Swedish, UK and Brazilian case studies considered.

A summary of biomass energy externality estimates is provided in Table 45 and Table 46. Ottinger et al. (1990) provide an estimate for the externalities of biomass energy based on the results of a previous study (ECO Northwest, 1986). The estimate is based on specific US biomass conventional co-generation facilities fuelled with pulp & paper mill waste, waste liquor and forest residues. The effects considered in this early study were health damages from particulates and CO emissions and visibility improvement as a result of avoided open burning of slash.

The Oak Ridge National Laboratory (ORNL) and Resources for the Future (RFF) study (ORNL/RFF, 1994) has been carried out as part of the EC/US External Costs of Fuel Cycles study, the first phase of the ExternE project (CEC, 1995), and focused on the use of wood residues for electricity generation using combustion and gasification technology at a specific site in the US. Another study, using a methodology similar to that of the ExternE study and focusing on human health impacts of atmospheric emissions, has been carried out as part of the New York State Externalities Study (RCG/Tellus, 1995).

Two studies have been carried out in Europe as part of the second phase of the ExternE project (CEC, 1995) by the Centro de Estudos em Economia da Energia, dos Transportes e do Ambiente (CEEETA, 1993 and Fernandes, 1995) and by the National Technical University of Athens (NTUA, 1995 and Diamantidis et al., 1996). These studies considered the use of forestry plantations, wood residues and energy crops at specific sites in Portugal and Greece. The ORNL/RFF, CEEETA and NTUA studies focused on the following priority impacts: public health, groundwater contamination from nitrogen leaching, soil erosion, occupational health, and road damage.

Another European effort to study the externalities of biomass energy has been carried out as part of the EU-APAS programme (Faaij et al., 1998 and Saez et al., 1998), and includes certain macroeconomic effects as externalities. More recently, the third phase of the ExternE project has included numerous biomass fuel cycle studies as part of the national implementation studies (CEC 1998a) (Table 45), and another EU project, known as the BioCosts project (CEC, 1998b), has focused on the economic and environmental performance of different biomass fuel cycles for power and automotive applications across the European Union (Table 46).

As in the case of fossil fuel cycles, human health effects of atmospheric emissions appear to dominate the externalities of biomass fuel cycles. This is in part due to the fact that human health impacts from atmospheric emissions are those on which most monetisation efforts have concentrated to date. In this respect, the externalities of the biomass production cycle associated with the local biosphere may in many cases be underestimated. These, however, need not necessarily be negative, for example biomass plantations for energy may provide an increase in biodiversity compared to alternative land uses.

Effects other than health impacts, where they are considered, are generally found to be small (CEC, 1998b). Such is the case of impacts of air emissions on agriculture, forests and materials (less than m€0.1/kWh in the BioCosts study and less than m€1.0/kWh in other studies cited in it), groundwater contamination from nitrogen leaching, soil erosion (only the ORNL/RFF study finds an effect of the same order of magnitude as health damages from air pollution, estimated at about m€1.0/kWh), occupational health (except for the CEEETA study which arrives at damages from road accidents of the same order of magnitude as health damages from atmospheric emissions, estimated at m€1.4-2.4/kWh) and road damages (although it is debatable whether this is actually an externality).

The range of external costs of nitrogen leaching from short rotation coppice appears significant (m€0.8-30/kWh) in a study analysing Dutch conditions (Faaij et al., 1998). However, the net effect of a biomass for energy plantation will depend on the alternative land use, and it may be beneficial if the alternative land use is for food crops or detrimental if the alternative land use is fallow land. The same study estimates the external costs of herbicide and pesticide use at m€0.8-9.9/kWh. The net effect of biomass for energy plantations will again depend on the alternative land use. These values do not represent damage costs of fertiliser and agrochemical use, but are based on WTP to reduce levels of nitrates in water and on a shadow price for herbicide and pesticide use based on reductions in yields associated with lower use. Other studies show much lower values for externalities associated with agrochemicals use (e.g. Saez et al. (1998) estimate them at m€0.06-0.4/kWh). Impacts of soil erosion can be significant (Saez et al., 1998), but the net effects of biomass plantations for energy with respect to alternative land use may be positive.

The variety of possible biomass sources, variations in practices used for the procurement of biomass and the influence of site specific considerations impose a careful examination of potential effects on soil, water, biodiversity and rural amenity. In the case of energy crops, potentially negative effects on soil and water can in many cases be avoided if attention is paid to site-specific considerations (e.g. nitrogen sensitive areas) and adequate agricultural practices are followed. The use of biomass for energy purposes is also not likely to negatively affect biodiversity. When considering energy crops such as short rotation coppice, it is believed that biodiversity is likely to benefit compared to alternative land uses. Rural amenity, principally in terms of visual amenity, can be a major issue. Where biomass energy schemes imply landscape changes, they may receive strong opposition from the public, which translates to high individual monetary preferences against biomass energy. However, opposition to the schemes can be dealt with through information and involvement of the local population.

While the impacts of small-scale exploitation of biomass are likely to be of little significance, large-scale exploitation of biomass for energy would require more careful consideration.

Environmental externalities have dominated the scene, but some studies have also addressed non-environmental issues. Faaij et al. (1998) consider the externalities associated with effects of fuel cycles on GDP and employment. The consideration of the effects of biomass (based on energy crops) and coal on GDP for the Netherlands leads to a significant net benefit for biomass (biomass GDP increment: m€6.0 - 15/kWh; coal GDP increment: m€(-6.9) - (-7.6)/kWh). Also with regard to employment, biomass presents benefits over coal in the Dutch situation (biomass employment benefit: m€0.8 – 4.0/kWh; coal employment benefits: m€0.3 - 1.5/kWh). Employment generation is often hailed as a potential benefit of renewable energy, biomass in particular. Overall, there is reason to believe that there is a net positive effect on employment from the use of biomass energy (CEC, 1998b), in particular for countries which rely heavily on energy imports and which possess a high rate of long-term unemployment.

The externalities of biomass energy vary much depending on the biomass fuel cycle, the conversion technology and the site considered. They appear to be generally low, about an order of magnitude lower than typical energy costs, and significantly lower compared to the externalities of most fossil fuel cycles. However, some studies present ranges with external costs of similar magnitude to the cost of energy production and to the externality associated with the better performing fossil fuel cycles (e.g. natural gas). Some studies have pointed out the potential significance of nitrogen leaching from fertiliser application, herbicide and pesticide use, soil erosion and road accidents. Potentially significant macro-economic benefits have been attributed to biomass energy in some cases. As for fossil fuel cycles, the dominant externality is attributed to health impacts of atmospheric emissions from the fuel cycle, in particular the conversion stage. Most impacts dealt with in the studies reviewed have been considered in the present study.

4 Externalities of the Värnamo plant biomass fuel cycle and reference systems

This section quantifies, where possible, significant externalities associated with the Värnamo plant biomass fuel cycle. The externalities valuation is based on the fuel cycle impacts and on the environmental analysis discussed in Chapters 4 and 5.

Acidification is an important issue in Sweden, in particular in the South (see Section 4.1 in Chapter 4 and Section 4.2 in Chapter 5). Based on an average forest residues availability of 30 odt/ha as a result of felling operations, it is estimated that between 150 and 200 kgN/ha is removed from the forest with the biomass fuel through residues collection. Fuel cycle activities are estimated to return to the forest, through atmospheric deposition of airborne pollutants about 10% of the nitrogen amount removed (Jörgensen et al., 1998). The resulting nitrogen removal rate for a plant of the Värnamo type is about 1 gN/kWh of energy (heat and electricity) produced. An indicative monetary value of the benefit of nitrogen removal can then be estimated by taking the Swedish NO_x-emissions levy of €14/kgN as a proxy for the willingness to pay for the reduction of the damage caused by nitrogen. The worst case scenario in which all nitrogen that is not removed from the forest is assumed to leach leads to an external benefit for the Värnamo plant of about m€14/kWh.

Deaths from road transport accidents may be a cause of concern in the case of biomass fuel transport. An indicative calculation of the externality, based on European statistics of road accidents and a statistical value of life of €3.1 million gives an externality associated with heavy goods vehicle transport of about m€0.054/kWh for the Värnamo plant (Scrase, 1998).

The economic impacts of employment and resource use are not treated as externalities in this study. However, these impacts may be significant and need to be considered by policy makers when comparing different sources of energy. If the creation of jobs results in the reduction of the long-term unemployed, it may be argued that it does result in an external benefit, but the actual benefit is difficult to assess as it will depend on the boundaries chosen and the structure of the economy. As discussed in Section 3 of Chapter 5, efficient biomass systems will aim at reducing labour requirements and overall little additional employment generation would result from biomass fuel cycles compared to conventional fuel cycles. Most benefits in terms of employment would result in countries which rely on imported fossil fuels. Depending on the structure of the economy, indirect employment generated by investments in sectors other than those directly involved in the biomass fuel cycle may also be significant. What is of particular importance with regard to employment when considering biomass fuel cycles are the sectors e.g. agriculture, and regions where jobs are created.

Resource use has an important impact on the national economy in the case of imported resources. The impact of resource use on the national balance of payments should not in itself be considered an externality, as it is reflected in economic effects such as employment and other multiplier effects within the economy. However, the macroeconomic effects can be significant, and will depend on the structure of the individual economies. In particular, the effect on the national economy is likely to be significant for countries switching from imported fossil fuels to indigenous biomass energy, but should be small for countries which rely on their own fossil fuels. Given the geographical distribution of fossil and biomass resources, many countries, Sweden for example, are likely to benefit from an increased exploitation of biomass energy.

Activities associated with forest residues collection are not likely to result in any significant external effects on biodiversity. Also, the fuel cycle is not likely to have any significant external effects on human amenity in terms of road congestion, noise, odours and recreational use of the forest. Although, odours were an issue at the Värnamo plant site because of the large annexed drying facility, any significant externality associated with them was internalised through the installation of a flue gas condensation system. The Swedish population attributes a high recreational value to Swedish forests (Jörgensen et al., 1998), and restrictions on its use as a source of recreation could lead to significant external effects. Most of the impact on recreation is due to logging and felling, which are not included in the system boundaries of this study since they are activities related to timber production. The collection of forest residues could improve access to the forest and can then possibly represent a benefit in terms of recreational use of the forest.

The review of externalities of energy discussed in the previous sections indicates that the impacts of atmospheric emissions from the fuel cycle, the conversion stage in particular, are likely to be significant. The externalities associated with the emissions from the Värnamo plant are calculated for two sites, Värnamo and Lauffen in Germany, using the EcoSense model. The Lauffen site has been used as a common site for comparing the externalities of different biomass and reference conversion technologies. The comparison of the calculations performed for the Lauffen site with those performed for the original sites will provide an indication of the site dependency of the results.

Table 48 and Table 49 summarise, for the different locations considered, the EcoSense input data for the biomass and reference fuel cycles and the external costs calculated for the health impact categories and pollutants considered by the model. A detailed description of the EcoSense model can be found in CEC (1995) and (1998a). Few human health impact categories account for the bulk of the damage, and the impact categories which make up over 99% of the damage costs are listed in the table. The damage estimates refer to for long-range dispersion, with local effects being of little importance. Calculations have also been performed for the impact categories considered by the model other than those pertaining to human health, such as damage to crops, forestry and buildings. These result to be of little significance compared to impacts on human health and are ignored.

Externality calculations focus on the main regulated pollutants: NO_x, SO_2 and PM. Differences in emissions between the biomass and reference systems, in particular with regard to the conversion stage, have been discussed in the environmental analysis in Chapter 5. In particular, the environmental analysis takes into account differences in emissions which are not reflected in the calculation of the externalities e.g. CO and NMHC. CO emissions appear to be greater for the biomass fuel cycle compared to the reference systems. Although, the levels of CO and NMHC emissions are low for the fuel cycles considered, they have potential effects on human health and should receive further consideration. CO_2 emissions are discussed in Sections 7 and 8.

For the purpose of the EcoSense modelling, the limit stated in the planning permission has been used for NO_x emissions from the biomass fuel cycle conversion stage and mid-range values of emission measurements performed by Bioflow Ltd have been used for PM and SO_2 emissions. Mid-range values have been used for emissions of all three pollutants from the other stages of the fuel cycle. The results are presented as best estimates, and a discussion on the uncertainty associated with the valuation of the different health category impacts can be found in CEC (1995) and (1998a) and in Krewitt et al. (1999).

The externality value associated with the conversion stage is about m€1.2/kWh, and it rises to m€1.5/kWh if all stages of the biomass fuel cycle are considered. The externalities of human health impacts represent a small percentage, about 4%, of the estimated cost of energy from early commercial plants of the Värnamo type (m€39.0/kWh for a 30 MW_e plant, a biomass fuel cost of €2.44/GJ and a discount rate of 10%). The externalities resulting from fuel cycle stages other than the conversion stage, in particular biomass production and transport, represent about 20% of the total fuel cycle externality. The externalities of the biomass fuel cycle are significantly lower compared to those of the reference systems which are calculated to be about m€7.2 and 5.8/kWh for all fuel cycle stages (m€5.5 and 5.6/kWh for the conversion stage) for systems 1 and 2 (see legend in Table 48), respectively. The higher externalities in the case of the reference systems are attributable mainly to the higher sulphur emissions. The externalities associated with NO_x and PM emissions are small in comparison. The elimination of fuel NO_x emissions from the conversion stage would significantly reduce the already low emissions, down to about a quarter of the imposed emission limit.

Location has an important effect on externalities. Siting the biomass and reference plants at Lauffen in Germany increases the value of the externalities considerably. The externalities are m€6.8/kWh for all fuel cycle stages (m€5.3/kWh for the conversion stage) for the biomass plant and m€30 and 25/kWh for all fuel cycle stages (m€22 and 24/kWh for the conversion stage) for reference systems 1 and 2, respectively. The increase in the externalities of about a factor 4 is a result of the emissions affecting areas with higher population densities.

Figure 41 and Figure 42 provide an illustration of the magnitude of the externalities for the different sites and fuel cycle stages and their breakdown according to impacts and pollutants.

Table 48: EcoSense input data and external costs of the high-pressure BIG/CC and reference systems at Värnamo, Sweden

Fuel		BIG/CC	BIG/CC	System1	System1	System2	System2
Location		Värnamo	Värnamo	Värnamo	Värnamo	Värnamo	Värnamo
Fuel-cycle stages		Conversion	All stages	Conversion	All stages	Conversion	All stages
EcoSense Data							
Net electricity capacity	MW	5.8	5.8	5.8	5.8	5.8	5.8
District heat capacity	MW	9	9	9	9	9	9
Full-load hours	h / a	4400	4400	4400	4400	4400	4400
SO_2 emissions	mg / Nm^3	21.0	21.6	491	641	641	642
NO_x emissions	mg / Nm^3	72.0	94	174	212	215	255
Particulate emissions	mg / Nm^3	2.0	4.6	7.0	15	7.0	15
Flue gas volume	Nm^3 / h	46600	46600	17300	17300	22600	22600
Flue gas temperature	K	403	403	403	403	382	382
Stack height	m	50	50	63	63	63	63
Stack diameter	m	1.4	1.4	1.1	1.1	1.1	1.1
Anemometer height	m	10	10	10	10	10	10
Geographical latitude	degree	57.11	57.11	57.11	57.11	57.11	57.11
Geographical longitude	degree	14.03	14.03	14.03	14.03	14.03	14.03
Elevation at site	m	300	300	300	300	300	300
Priority Impacts (99%)							
Chronic YOLL	m€/kWh	0.91	1.2	3.3	4.3	3.5	3.7
Asthma	m€/kWh	0.070	0.070	0.78	1.0	0.82	0.82
Chronic bronchitis	m€/kWh	0.066	0.085	0.23	0.31	0.25	0.26
Restricted activity days	m€/kWh	0.024	0.031	0.089	0.12	0.093	0.10
Acute YOLL	m€/kWh	0.069	0.087	0.33	0.43	0.11	0.11
Bronchodilator usage	m€/kWh	0.0033	0.0042	0.012	0.016	0.013	0.013
Malignant neoplasm	m€/kWh	0.062	0.063	0.69	0.90	0.73	0.73
Sum (0% discounting)	*m€/kWh*	1.2	1.5	5.5	7.1	5.5	5.8
Pollutants							
Nitrates	m€/kWh	0.73	0.97	0.71	0.86	0.74	0.93
Sulphates	m€/kWh	0.40	0.40	4.5	5.80	4.7	4.7
NO_x	m€/kWh	0.037	0.048	0.056	0.067	0.018	0.021
SO_2	m€/kWh	0.012	0.013	0.20	0.26	0.069	0.069
Particulates	m€/kWh	0.037	0.085	0.079	0.17	0.064	0.14
Sum (0% discounting)	*m€/kWh*	1.2	1.5	5.5	7.2	5.6	5.8

System 1: Electricity and heat from CFB coal plant and additional electricity from hydropower
System 2: Electricity and heat from CFB coal plant and additional electricity from CCGT

Table 49: EcoSense input data and external costs of the high-pressure BIG/CC and reference systems at Lauffen, Germany

Fuel		BIG/CC	BIG/CC	System1	System1	System2	System2
Location		Lauffen	Lauffen	Lauffen	Lauffen	Lauffen	Lauffen
Fuel-cycle stages		Conversion	All stages	Conversion	All stages	Conversion	All stages
EcoSense Data							
Net electricity capacity	MW	5.8	5.8	5.8	5.8	5.8	5.8
District heat capacity	MW	9	9	9	9	9	9
Full-load hours	h / a	4400	4400	4400	4400	4400	4400
SO_2 emissions	mg / Nm^3	21.0	21.6	491	641	641	642
NO_x emissions	mg / Nm^3	72.0	94	174	212	215	255
Particulate emissions	mg / Nm^3	2.0	4.6	7.0	15	7.0	15
Flue gas volume	Nm^3 / h	46600	46600	17300	17300	22600	22600
Flue gas temperature	K	403	403	403	403	382	382
Stack height	m	50	50	63	63	63	63
Stack diameter	m	1.4	1.4	1.1	1.1	1.1	1.1
Anemometer height	m	10	10	10	10	10	10
Geographical latitude	degree	49.08	49.08	49.08	49.08	49.08	49.08
Geographical longitude	degree	9.18	9.18	9.18	9.18	9.18	9.18
Elevation at site	m	165	165	165	165	165	165
Priority Impacts (99%)							
Chronic YOLL	m€/kWh	4.3	5.6	15	19	15	17
Asthma	m€/kWh	0.20	0.20	3.0	4.0	3.3	3.3
Chronic bronchitis	m€/kWh	0.31	0.41	0.31	1.3	1.1	1.2
Restricted activity days	m€/kWh	0.11	0.15	0.39	0.51	0.41	0.44
Acute YOLL	m€/kWh	0.14	0.18	0.62	0.79	0.57	0.68
Bronchodilator usage	m€/kWh	0.015	0.020	0.05	0.069	0.055	0.059
Malignant neoplasm	m€/kWh	0.18	0.17	2.7	3.5	2.9	2.9
Sum (0% discounting)	*m€/kWh*	5.3	6.8	22	29	24	25
Pollutants							
Nitrates	m€/kWh	3.8	5.0	4.3	5.2	4.3	5.3
Sulphates	m€/kWh	1.1	1.1	17	23	18	18
NO_x	m€/kWh	0.085	0.11	0.12	0.15	0.13	0.15
SO_2	m€/kWh	0.028	0.029	0.40	0.52	0.43	0.43
Particulates	m€/kWh	0.23	0.54	0.49	1.1	0.40	0.86
Sum (0% discounting)	*m€/kWh*	5.3	6.8	22	30	24	25

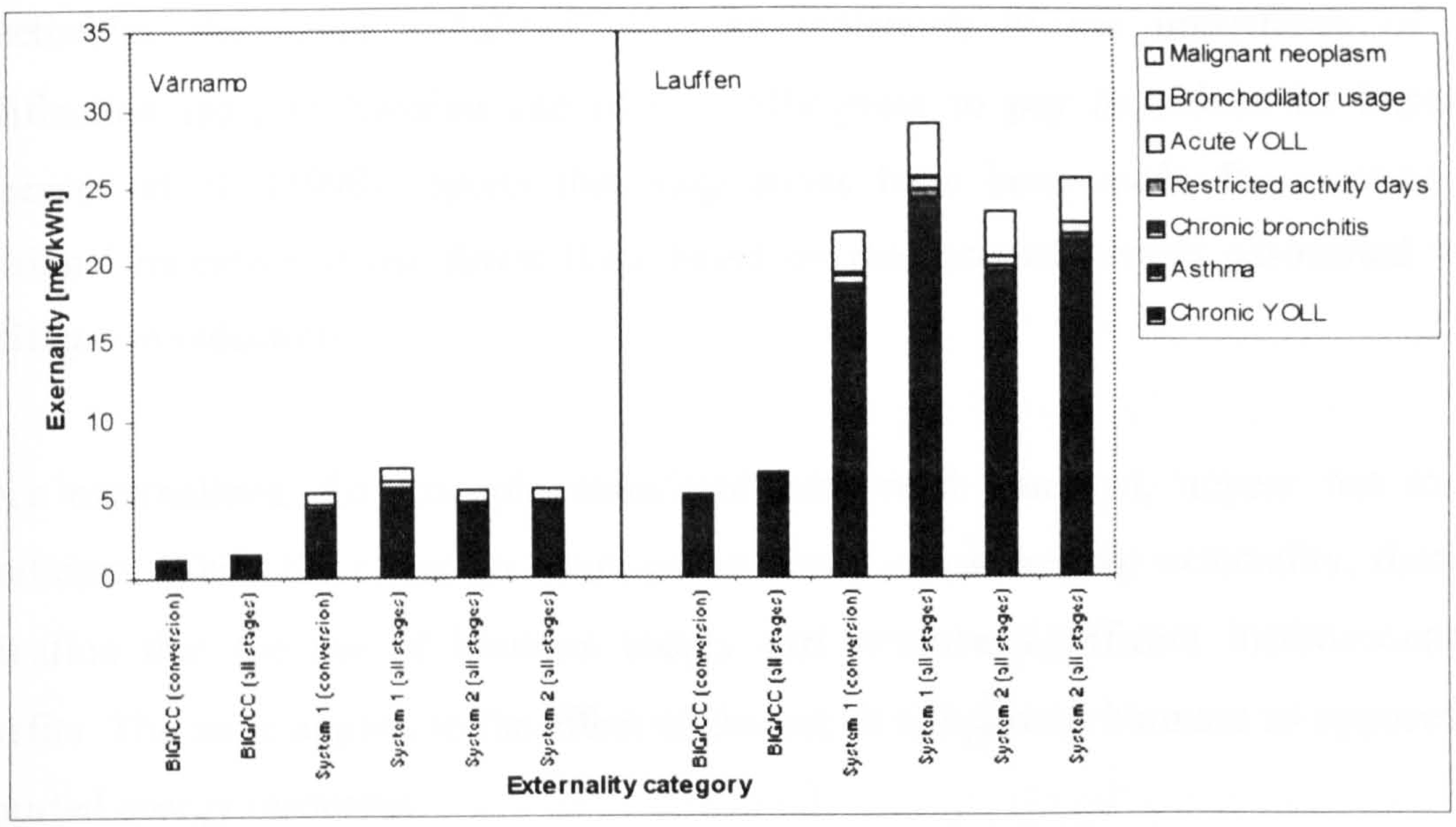

Figure 41: External costs of the Värnamo high-pressure BIG/CC plant with respect to human health impacts in m€/kWh

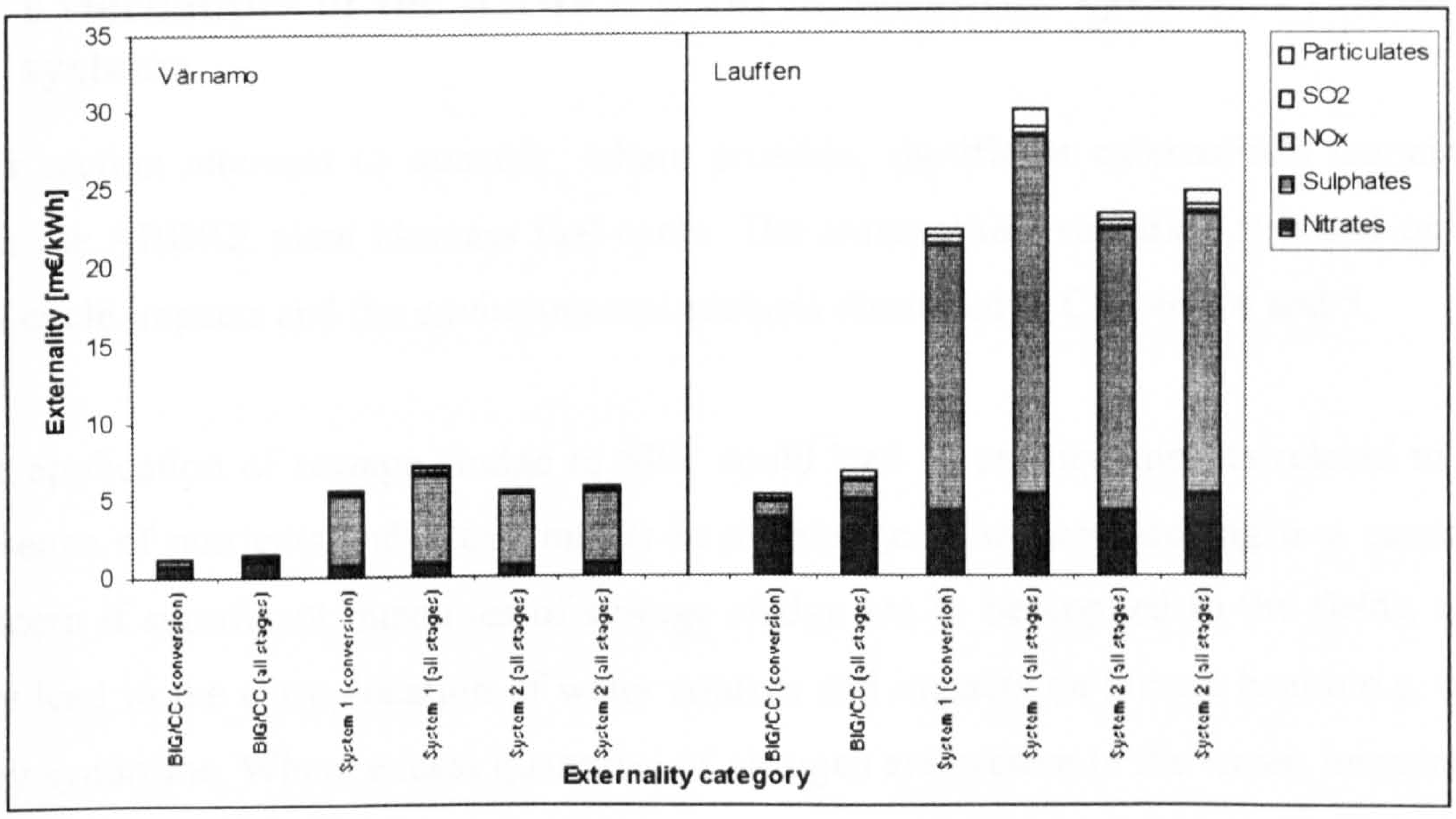

Figure 42: External costs of the Värnamo high-pressure BIG/CC plant with respect to air pollutants in m€/kWh.

The external costs of the reference systems are about a factor 4 higher than those of the biomass fuel cycle. The external costs associated with atmospheric emissions are found to vary considerably according to location, and they are factor 4 higher for the Lauffen site compared to the Värnamo site.

The reduction in acidification resulting from forest residues collection appears to result in a significant external benefit. However, the use of the Swedish NO_x emissions levy to calculate the external benefit does not provide an actual estimate of the avoided damage since the levy is based on a standard price approach rather than a damage cost valuation.

Nonetheless, the value calculated gives an indication of the importance of the acidification issue in Sweden and of the willingness to pay to reduce its impacts. Jörgensen et al. (1998) reports that suggestions have been made for creating an additional incentive to use forest fuels based on the external benefit associated with acidification reduction.

Other externalities, for example associated with road transport, appear not to be significant. While the effect on employment is not considered an externality, there is indication that the use of biomass energy can produce significant macroeconomic benefits. The same applies to the effect of the use of indigenous biomass as opposed to imported energy resources.

5 Externalities of the ARBRE plant biomass fuel cycle and reference systems

This section attempts to quantify, where possible, significant externalities associated with the ARBRE plant biomass fuel cycle. The externalities valuation is based on the fuel cycle impacts and the environmental analysis discussed in Chapters 4 and 5.

The application of sewage sludge to SRC could lead to priority impacts related to the presence of nutrients and heavy metals in the sludge. Nitrogen leaching is a cause of concern if significant quantities of sewage sludge are to be applied to the fields, as it may lead to the eutrophication of water courses and impacts on human health e.g. blue baby syndrome. Where excess quantities of nitrogen are present in the water, impacts on human health will generally be avoided at the expense of increased costs in the supply of drinking water. The application of sewage sludge to the fields will be constrained by regulatory limits on levels of nitrogen applied. Areas where nitrogen leaching will pose a threat will be classified as NVZs and a limit on 170 kgN/ha/yr will be enforced (see Section 4.4 in Chapter 5). An upper limit for the externality associated with nitrogen leaching in NVZs can be estimated by assuming a maximum nitrogen leaching equal to the 170 kgN/ha/yr applied. The external cost associated with nitrogen leaching is calculated based on a range of costs for reducing nitrate concentration in groundwater treated for public drinking water estimated at €0.65 - 6.6/kg of nitrate (€2.2 - 22.6/kg N) (CEEETA, 1993 and NTUA, 1995). The upper limit for nitrogen leaching in the case of an ARBRE type is estimated at 0.0085 kg N/kWh. An upper limit for the externality would then be m€19 - 190/kWh. The calculation indicates that the externality associated with nitrogen leaching is potentially large, and that even the leaching of a fraction of the nitrogen applied could lead to a significant externality.

The build up of heavy metals in the soil is also a cause of concern when applying sewage sludge to fields, cadmium being the metal of greatest concern. However, based on the environmental analysis in Chapter 5, heavy metals added to the fields through the application of sewage sludge are likely to be well below UK regulatory limits. Also, SRC willow selectively takes up heavy metals, cadmium in particular (Riddell-Black et al. 1996a), and may then be regarded as having a beneficial effect on soil quality by limiting the build up of noxious metals. No direct monetary valuation of the impacts of heavy metals present in the soil has been found in the literature. An approach to valuing the possible benefits of cadmium removal by SRC is presented by Börjesson (1999), who takes a value of about €3.2 (SEK30) per gramme of cadmium based on the Swedish tax on the cadmium content of fertilisers. Assuming a yield of 10 odt/ha/yr for SRC, he estimates the net reduction in cadmium concentration in the upper soil from SRC uptake at 6 g/ha/yr. After considering the cost of cadmium removal from the ash, about €7.0/t, and the fertiliser value of the clean ash, about €5.4/t, he values the net benefit of cadmium removal by SRC at about €3.0/g, corresponding to €18.0/ha/yr.

In the case of the ARBRE project, a net cadmium reduction in the soil equal to the value provided by Börjesson (6 g/ha/yr) is assumed if sludge is applied to SRC instead of other agricultural land. The original figure for the net benefit of cadmium removal of €3.2/g of cadmium is more appropriate than the adjusted figure of about €3.0/g, if the ash is disposed to landfill rather than treated and used as fertiliser. Then, an external benefit of about €19.3/ha/yr or €0.11/GJ of biomass fuel could be ascribed to the removal of cadmium by SRC. It should be noted that the private costs at some stage of the fuel cycle should take into account any additional cost incurred by ash disposal. As a comparison, the cost of SRC production for the ARBRE project is estimated to range between €195 and 524/ha/yr. The external benefit for an ARBRE type plant associated with cadmium removal would then be about m€0.95/kWh.

SRC is characterised by a high water use which could have a significant impact on groundwater recharge and stream flow. The impact of water pollutants, principally nitrates, would be exacerbated by a lower dilution rate. The greatest economic impacts will be in dry areas where groundwater is the major source of drinking water and the economic damages could be measured in terms of higher costs for potable water supply. The reduction in stream flow could also affect the recreation value of rivers. In the case where sewage sludge is applied to the fields, its water content somewhat reduces the potential impacts of water use. Where a source exceeds the EU limit of 11.3 mg/l NO_3-N a less polluted source must be found to dilute it before it can be supplied to customers. Thus, the fewer unpolluted streams or aquifers that are available, the greater the cost of drinking water supply. Hall et al. (1996) contains useful information which could allow some economic valuation of the hydrological impacts of SRC plantations. However, the impacts are very site-specific. They depend on the effective precipitation, presence or absence of aquifers, soil type and the availability of alternative supplies of drinking water. The impacts of water use have not been assessed in detail, however, SRC should be sited and managed as to avoid any significant impacts.

Road transport of biomass is another potential source of priority impacts. In the case of the ARBRE plant the externality associated with biomass fuel transport is found to be about m€0.11/kWh of useful energy generated (Scrase, 1998). The impact of road transport may be significant in terms of rural amenity, but no attempt has been made to quantify such impact. Road transport has not been a cause of public opposition in the case of the Värnamo and ARBRE plants. However, the issue may need more careful consideration, in particular for future larger biomass schemes.

The same discussion on employment and resource use as for the Värnamo case study applies to the ARBRE case study.

Biomass energy from SRC is not likely to have significant effects on biodiversity and on human amenity in terms of road congestion, noise, odours, visual impacts and recreational use of the countryside if it remains within a sensible scale. Marginal benefits are most likely to result from SRC compared to conventional agriculture, with regard to biodiversity and recreational aspects (see Sections 4.5 and 4.6 in Chapter 5).

Similarly to the Värnamo plant biomass fuel cycle, the atmospheric emissions from the ARBRE fuel cycle, in particular from the conversion stage, represent a significant externality. The impacts of the fuel cycle atmospheric emissions and their monetary value have been estimated for the original site, Eggborough, and for the Lauffen site in Germany using the EcoSense model.

Table 50 and Table 51 summarise, for the different locations considered, the EcoSense input data for the biomass and reference fuel cycles and the external costs calculated for the health impact categories and pollutants considered by the model. As for the Värnamo plant, few human health impact categories account for the bulk of the damage, and the impact categories which make up over 99% of the damage costs are listed in the tables. Calculations have been performed as well for the other impact categories considered by the model, such as damage to crops, forestry and buildings, and are found to be of little significance compared to impacts on human health.

Externality calculations focus on the main regulated pollutants: NO_x, SO_2 and PM. Differences in emissions between the biomass and reference systems, in particular with regard to the conversion stage, have been discussed in the environmental analysis in Chapter 5. In particular, the environmental analysis takes into account differences in emissions which are not reflected in the calculation of the externalities e.g. CO and NMHC. As for the Värnamo plant, CO emissions appear to be greater for the biomass fuel cycle compared to the reference coal and gas fuel cycles. Although, the levels of CO and NMHC emissions are low for the fuel cycles considered, they have potential effects on human health and should receive further consideration. CO_2 emissions are discussed in Sections 7 and 8.

The mid-range value of the externality associated with the conversion stage is about m€2.5/kWh, and it rises to m€6.0/kWh if all stages of the biomass fuel cycle are considered. The fuel cycle externality represents about 13% of the estimated cost of electricity from early commercial plants of the ARBRE type (m€46.8/kWh for a 30 MW_e plant, a biomass fuel cost of €2.53/GJ and a discount rate of 10%). The externalities of the biomass fuel cycle are significantly lower than those of the reference coal fuel cycle (m€29/kWh), a pulverised coal combustion plant (system 1), and similar to those of the reference gas fuel cycle (system 2) (m€7/kWh). The contribution of fuel cycle stages other than the conversion stage accounts for more than half of the externality estimated for the biomass fuel cycle. Hence, the importance of reducing the emissions of the biomass production and transport stages. Essentially all externalities associated with atmospheric emissions in the case of the reference fossil fuel cycles result from the conversion stage. The higher externalities in the case of the reference coal fuel cycle are attributable to the higher emissions of the three pollutants modelled, NO_x, SO_2 and PM, while for the reference gas fuel cycle the higher externality is attributable to higher NO_x emissions from the CCGT plant. The differences in emissions between the biomass and reference coal fuel cycle are greater for the UK case study compared to the Swedish one because of the more modern reference coal technology considered for Sweden and the lower fuel NO_x emissions for the ARBRE plant compared to the Värnamo plant.

The externalities per unit of useful energy generated are lower for the Värnamo plant because of its combined generation of heat and electricity compared to the ARBRE plant which generates electricity only. If the two plants were to generate an equal amount of useful energy, then the conversion stage externalities could be lower for the ARBRE type plant because of its possibly lower NO_x emissions. However, the externalities from the biomass production stage are likely to be greater for the ARBRE fuel cycle because of the more intensive activities associated with SRC compared to forest residues. Overall the emissions from both biomass fuel cycles are likely to be similar.

Again, location has an important effect on externalities. Siting the biomass and reference plants at Lauffen in Germany increases the value of the externalities considerably. The values rise to m€12.6/kWh (m€5.6/kWh for the conversion stage) for the biomass fuel cycle, m€67/kWh (m€66/kWh for the conversion stage) for the coal fuel cycle and m€19/kWh (m€18/kWh for the conversion stage) for the natural gas fuel cycle. The externalities increase by a factor 2.5 when siting the plants at Lauffen, because of the emissions affecting areas with higher population densities. The increase in externality is lower to that obtained for the Swedish case study because of the larger population affected by a plant sited in Eggborough compared to Värnamo.

Figure 43 and Figure 44 provides an illustration of the magnitude of the externalities for the different sites and fuel cycle stages and their breakdown according to impacts and pollutants.

Table 50: EcoSense input data and external costs of the low-pressure BIG/CC plant at Eggborough, UK.

Fuel		BIG/CC	BIG/CC	System1	System1	System2	System2
Location		Eggborough	Eggborough	Eggborough	Eggborough	Eggborough	Eggborough
Fuel-cycle stages		Conversion	All stages	Conversion	All stages	Conversion	All stages
EcoSense Data							
Gross electricity capacity	MW	10	10	8	8	8	8
Net electricity capacity	MW	8	8	8	8	8	8
Full-load hours	h / a	7450	7450	7450	7450	7450	7450
SO_2 emissions	mg / Nm^3	3.0	3.9	297	297.1	0	5.9
NO_x emissions	mg / Nm^3	36	77.5	650	657.4	299.2	308.7
Particulate emissions	mg / Nm^3	2.0	7.6	50	59.0	0	0
Flue gas volume	Nm^3 / h	62100	62100	28800	28800	28800	28800
Flue gas temperature	K	345	345	345	345	345	345
Stack height	m	41	41	240	240	65	65
Stack diameter	m	1.4	1.4	10	10	1.4	1.4
Anemometer height	m	10	10	10	10	10	10
Geographical latitude	degree	53.70	53.70	53.70	53.70	53.70	53.70
Geographical longitude	degree	-1.05	-1.05	-1.05	-1.05	-1.05	-1.05
Elevation at site	m	15	15	15	15	15	15
Priority Impacts (99%)							
Chronic YOLL	m€/kWh	2.1	5.1	22	22	6.0	6.3
Asthma	m€/kWh	0.031	0.011	1.6	1.6	-0.081	-0.051
Chronic bronchitis	m€/kWh	0.16	0.37	1.6	1.6	0.44	0.46
Restricted activity days	m€/kWh	0.057	0.14	0.57	0.59	0.16	0.17
Acute YOLL	m€/kWh	0.11	0.23	0.84	0.85	0.37	0.39
Bronchodilator usage	m€/kWh	0.0077	0.018	0.077	0.064	0.022	0.023
Malignant neoplasm	m€/kWh	0.028	0.010	1.4	1.4	-0.073	-0.046
Sum (0% discounting)	*m€/kWh*	2.5	5.9	28	28	6.9	7.2
Pollutants							
Nitrates	m€/kWh	1.8	3.9	14	15	7.0	7.3
Sulphates	m€/kWh	0.18	0.062	8.9	8.9	-0.46	-0.29
NO_x	m€/kWh	0.088	0.19	0.45	0.46	0.34	0.35
SO_2	m€/kWh	0.0075	0.010	0.25	0.25	-0.00073	0.0068
Particulates	m€/kWh	0.48	1.8	3.6	4.3	0	0
Sum (0% discounting)	*m€/kWh*	2.5	6.0	28	29	6.9	7.3

System 1: pulverised coal combustion plant fuel cycle
System 2: combined cycle gas turbine fuel cycle

Table 51: EcoSense input data and external costs of the low-pressure BIG/CC plant at Lauffen, Germany

Fuel Location Fuel-cycle stages		BIG/CC Lauffen Conversion	BIG/CC Lauffen All stages	System1 Lauffen Conversion	System1 Lauffen All stages	System2 Lauffen Conversion	System2 Lauffen All stages
EcoSense Data							
Gross electricity capacity	MW	10	10	8	8	8	8
Net electricity capacity	MW	8	8	8	8	8	8
Full-load hours	h / a	7450	7450	7450	7450	7450	7450
SO_2 emissions	mg / Nm^3	3.0	3.9	297	297.1	0	5.9
NO_x emissions	mg / Nm^3	36	77.5	650	657.4	299.2	308.7
Particulate emissions	mg / Nm^3	2.0	7.6	50	59.0	0	0
Flue gas volume	Nm^3 / h	62100	62100	28800	28800	28800	28800
Flue gas temperature	K	345	345	345	345	345	345
Stack height	m	41	41	240	240	65	65
Stack diameter	m	1.4	1.4	10	10	1.4	1.4
Anemometer height	m	10	10	10	10	10	10
Geographical latitude	degree	49.08	49.08	49.08	49.08	49.08	49.08
Geographical longitude	degree	9.18	9.18	9.18	9.18	9.18	9.18
Elevation at site	m	165	165	165	165	165	165
Priority Impacts (99%)							
Chronic YOLL	m€/kWh	4.83	11	52	53	16	16
Asthma	m€/kWh	0.038	0.013	3.6	3.6	-0.17	-0.098
Chronic bronchitis	m€/kWh	0.35	0.80	3.7	3.8	1.1	1.2
Restricted activity days	m€/kWh	0.13	0.29	1.4	1.4	0.42	0.43
Acute YOLL	m€/kWh	0.15	0.31	1.5	1.5	0.53	0.55
Bronchodilator usage	m€/kWh	0.017	0.040	0.18	0.19	0.056	0.059
Malignant neoplasm	m€/kWh	0.034	0.012	3.2	3.2	-0.15	-0.087
Sum (0% discounting)	*m€/kWh*	5.5	12.5	65	67	17	18
Pollutants							
Nitrates	m€/kWh	4.7	10	38	39	18	19
Sulphates	m€/kWh	0.22	0.075	20	20	-0.94	-0.55
NO_x	m€/kWh	0.10	0.23	0.75	0.75	0.43	0.44
SO_2	m€/kWh	0.010	0.013	0.41	0.41	0	0.0095
Particulates	m€/kWh	0.57	2.2	5.8	6.8	0	0
Sum (0% discounting)	*m€/kWh*	5.6	12.6	66	67	18	19

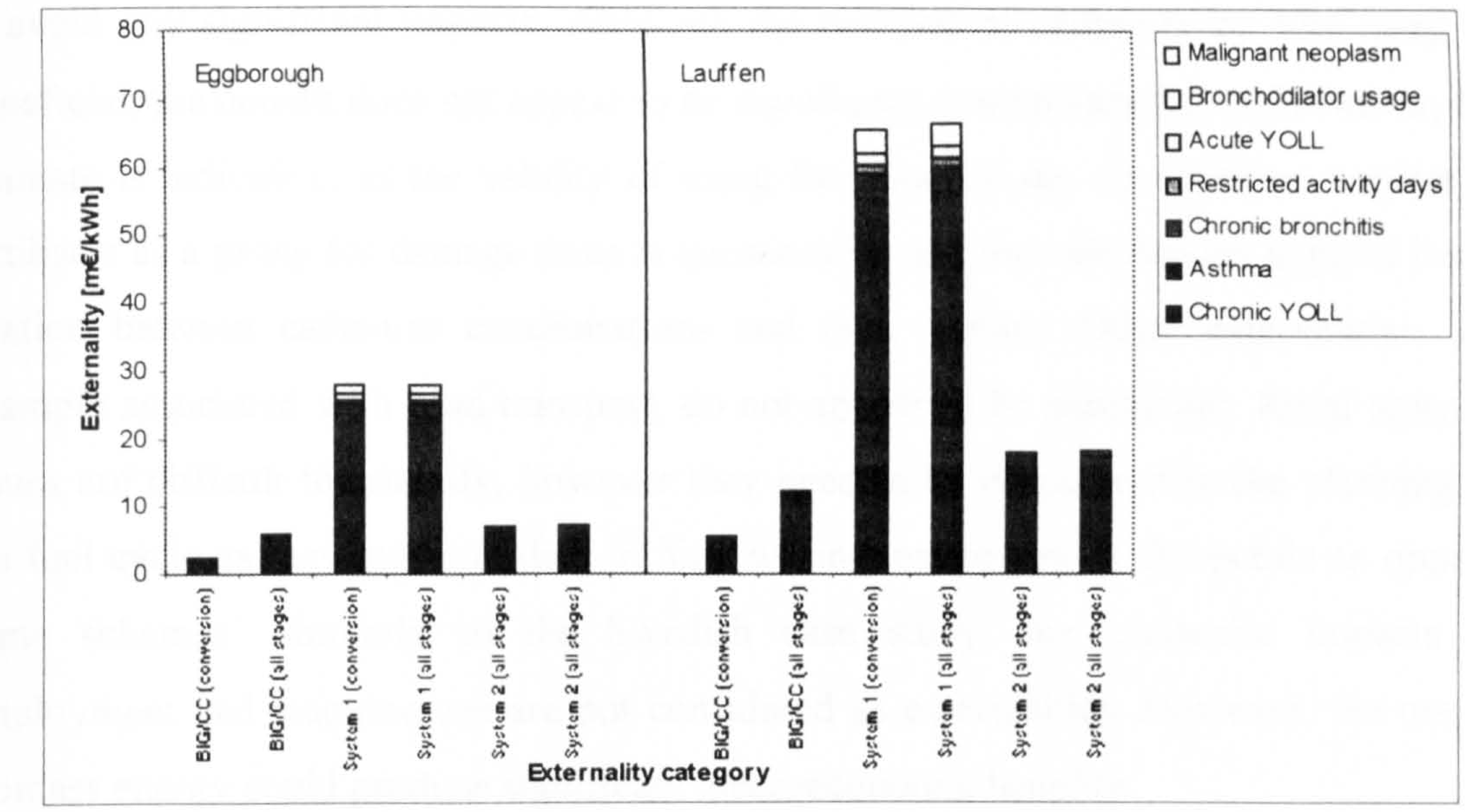

Figure 43: External costs of the low-pressure BIG/CC ARBRE plant with respect to human health impacts in m€/kWh.

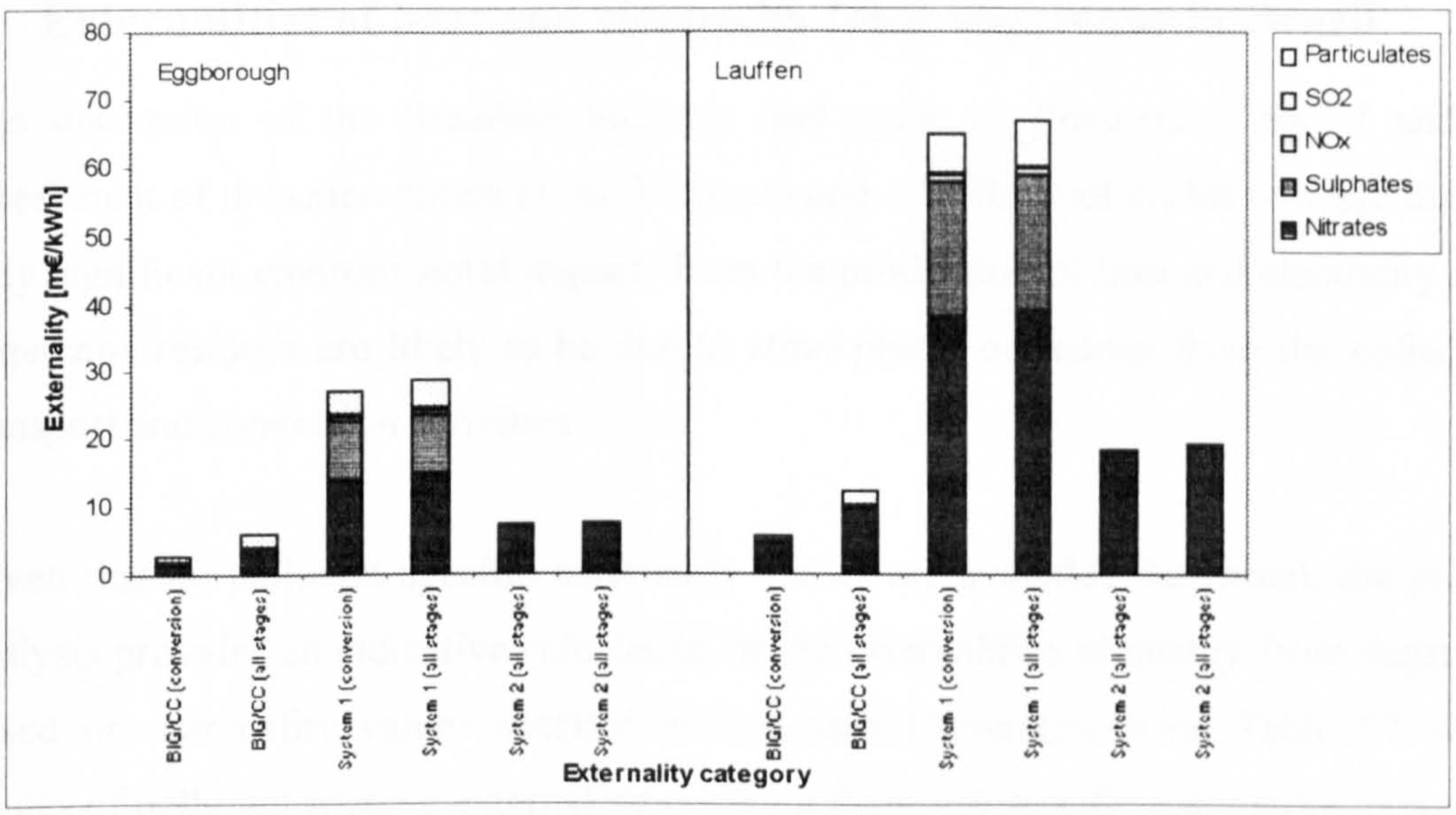

Figure 44: External costs of the low-pressure BIG/CC ARBRE plant with respect to air pollutants in m€/kWh.

The above discussion indicates that the external costs of the biomass fuel cycle are dominated by the damages associated with the health impacts of atmospheric emissions. Most damage is associated with NO_x emissions from the production, transport and conversion stages. The emissions from biomass production and transport contribute over half of the total damage costs, hence their reduction could significantly reduce the damage costs. The external costs of the biomass fuel cycles are much lower compared to those of the coal fuel cycle and a bit lower compared to those of the natural gas fuel cycle. Nitrogen leaching in the case of the UK biomass fuel cycle could result in a significant external cost. Good practice in the application of sewage sludge is essential to avoid any significant impacts. Although the removal of cadmium by SRC may be beneficial, the benefit does not appear to be significant in monetary terms. However, the estimate is indicative, as the validity of using the Swedish tax on cadmium content in fertilisers as a proxy for damage costs is questionable and the calculations imply a linear relation between cadmium concentrations and their impact. Other externalities, for example associated with road transport, do not appear to be significant. Rural amenity issues are difficult to quantify, however they need to be considered in the planning of the fuel cycle as they may translate to high willingness to pay of the public to oppose some schemes. Similarly to the Swedish case study, the economic impacts of employment and resource use are not considered as externalities. However, the use of biomass energy could produce significant macroeconomic benefits.

6 Externalities of heat and electricity from sugarcane in Brazil

The discussion of the Brazilian biomass fuel cycle in Chapters 6 and 7 and the assessment of the externalities of the Värnamo and ARBRE fuel cycles indicate that the only significant environmental impacts from the production of heat and electricity from sugarcane residues are likely to be due to atmospheric emissions from the collection, transport and conversion activities.

Given that no pollutant specific externality values are available for Brazil, the present analysis provides an indicative calculation of the externalities of energy from sugarcane based on externality values specific to European Union countries. Table 52 shows ranges of pollutant specific externalities derived from site specific externality valuations in 5 European Union countries (Sweden, UK, Portugal, Denmark, Germany) (CEC, 1998b), including those obtained for the Värnamo and ARBRE case studies discussed in the previous sections. The externalities are mainly a result of impacts on human health of the long-range dispersion of pollutants. Damage costs associated with CO_2 are treated separately and are discussed in Sections 7 and 8.

Table 52: Ranges of pollutant-specific externalities for Europe (CEC, 1998b)

Pollutant	Externality [€/kg]
NO_x	3.0 – 17.7
SO_2	6.1 – 12.6
PM	3.9 – 23.4

Table 53 compares emissions from a BIG/CC co-generation system fuelled with sugarcane residues (bagasse and harvest residues) with the reference system defined in Section 8 in Chapter 6. It is then possible to provide an indication of the external costs and benefits of using BIG/CC in place of the reference system based on the NO_x, SO_2 and PM emissions provided in Table 44 in Chapter 7.

Table 53: Indicative external costs and benefits of BIG/CC and reference systems for Brazil [m€/kWh]

	External costs [m€/kWh]	
	System 1	*System 2*
NO_x	0.4 - 2.5	1.4 - 9.2
SO_2	0.02 - 0.04	0.06 - 0.1
PM	0.04 - 0.2	0.04 - 0.2
Total	0.5 - 2.7	1.5 - 9.5

System 1: LP-BIG/CC system fuelled with bagasse and harvest residues
System 2: Biomass combustion system fuelled with bagasse to supply mill's energy needs and CCGT to supply additional electricity to match surplus electricity from system 1

The benefits to be gained by the introduction of BIG/CC systems are likely to be significant because of reduced externalities from co-generation at the mill site and from electricity generation in CCGT plants.

7 Damage costs of CO_2 emissions

Damage costs attributed to CO_2 emissions are characterised by very large uncertainty and vary greatly in the literature. Their estimation is a contentious issue, and the difficulties associated with it are discussed in Chapter 2. Eyre et al. (1997) have estimated a damage cost range between €20 and 55/tCO_2 as part of the ExternE project (CEC, 1998a). Based on this range, indicative damage costs have been calculated for the Swedish, UK and Brazilian biomass and reference systems (Table 54). The CO_2 damage costs appear to be of the same order of magnitude as the damage costs from regulated pollutants modelled with EcoSense, and the benefits of BIG/CC systems compared to the reference systems are likely to be large. However, the uncertainty over CO_2 damage costs renders their use impractical with regard to decision and policy-making.

Table 54: Damage cost estimates for CO_2 emissions from biomass and reference systems [m€/kWh]

	BIG/CC	System 1*	System 2*
Sweden[1]	0.18 – 0.5	6.5 – 18	7.3 – 20
UK[2]	1.2 – 3.2	16 – 44	6.2 – 17
Brazil[1]	0.012 – 0.034	3.2 – 9	

[1] systems produce heat and electricity
[2] systems produce electricity only
* for definition of systems see footnotes in Table 48, Table 50 and Table 53

Fuel cycles with low CO_2 emissions reduce the risk of damages from climate change, but the market introduction of fuel cycles such as BIG/CC involves a private cost premium compared to the use of conventional fuel cycles. To pay this cost premium may be sensible based on a precautionary approach aiming at reducing the risk of future damages associated with climate change and as a means of promoting the commercialisation of cleaner technologies.

The growing consensus over the risks of climate change has lead to increasing political commitment to reduce the emissions of greenhouse gases. However, decision and policy-making needs to account for the uncertainties underlying the climate change issue and reduce the economic risks of actions taken. It is then interesting to determine the additional costs, if any, associated with a reduction in CO_2 emissions as a result of replacing conventional energy sources with future commercial BIG/CC systems.

The following section discusses the additional cost incurred to reduce CO_2 emissions associated with the use of gasification-based biomass fuel cycles as opposed to conventional fossil-based fuel cycles, the so-called 'avoidance cost'.

8 Avoidance costs of CO_2 emissions

The avoidance cost is defined as the cost of biomass energy minus the cost of energy from the reference energy system, the difference divided by the net CO_2 emissions avoided. The avoidance cost can serve as a point of comparison with the damage cost estimates and with costs associated with alternative options for avoiding CO_2 emissions or mitigating the impacts of emissions.

The economic analysis of the Swedish case study (Chapter 5) shows that co-generation of electricity and district heat from BIG/CC fuelled with forestry residues can be competitive with coal based co-generation using modern CFB combustion. Therefore it may be possible to reduce CO_2 emissions at no additional cost. Similarly, the Brazilian case study indicates that surplus electricity could be exported from an average size sugarcane processing plant, using BIG/CC for co-generation, at a cost similar to that of the marginal cost of generating electricity from natural gas (c. m€30/kWh), based on an energy cost allocation. The costs of avoiding CO_2 emissions by implementing BIG/CC systems are of relevance mainly for the UK case study where electricity from BIG/CC fuelled with SRC is likely to remain more costly in the short-term compared to electricity from coal or natural gas. For example, based on the economic analysis in Chapter 5, the cost of electricity from a commercial 30 MW_e BIG/CC plant could be about m€42.5/kWh, compared to m€38.5/kWh for electricity from coal and m€25.9/kWh for electricity from natural gas. The avoidance costs of an ARBRE type fuel cycle, in the short-term, relative to the reference coal and gas fuel cycles are shown in Table 55, exclusive and inclusive of the externalities associated with other atmospheric emissions calculated for the Eggborough site. A negative value indicates that CO_2 emission can be avoided at a net social benefit.

Table 55: Avoidance cost of CO_2 emissions based on electricity generation from BIG/CC fuelled with SRC compared to coal and natural gas [€/tCO_2].

Reference fuel cycle	Avoidance cost (excluding externalities*)		Avoidance cost[1] (including externalities*)	
	30 MW_e BIG/CC	60 MW_e BIG/CC	30 MW_e BIG/CC	60 MW_e BIG/CC
UK coal	6.4 - 21.9	0.3 - 9.6	-17.0 - (-1.6)	-23.2 - (-13.9)
UK gas	48.5 - 111	30.5 - 75.8	44.6 - 107	26.6 - 71.9

Note: the low avoidance cost values relate to a low discount rate (5%) and the high avoidance cost values relate to a high discount rate (15%)

* the externalities considered here are those estimated for NO_x, SO_2 and PM using the EcoSense model

1 it should be noted that the case for biomass would be strengthened for plants sited at locations resulting in higher externalities from regulated pollutants e.g. Lauffen site

The CO_2 avoidance cost associated with the replacement of conventional electricity by biomass electricity in the UK depends on the discount rate used for calculating the private cost of energy and on the capacity of the BIG/CC plant because of economies of scale. The comparison between biomass and coal electricity indicates that CO_2 emissions could be avoided at very low cost under certain circumstances (large BIG/CC plant and low discount rate) and generally at costs below the damage cost estimates calculated in CEC (1998a). Internalisation of the externalities associated with regulated pollutants (NO_x, SO_2 and PM) shows that switching to biomass could lead to a net social benefit. The CO_2 avoidance cost associated with the replacement of CCGT electricity by BIG/CC electricity is high, but remains within the range of the damage cost estimates cited in the literature (IPCC, 1996).

9 Total costs and benefits of biomass and reference fuel cycles

The determination of the total costs and benefits of fuel cycles is restrained by lack of data, insufficient knowledge on the impacts and value judgements. To wish to calculate the actual total costs is an unrealistic endeavour.

This chapter has provided an assessment of significant externalities for the biomass and reference fuel cycles considered. Although, lack of information does not allow a proper assessment of the externality in some cases e.g. externalities of nitrogen leaching and cadmium removal, indicative values have been calculated to give an idea of their magnitude. In the case of forest residues, for example, it appears that the benefit of nitrogen removal from forests in areas prone to acidification could translate into a significant economic benefit associated with biomass energy. In a similar way, nitrogen leaching from SRC fields could lead to significant external costs which could negatively affect the competitiveness of biomass energy, hence the need for precautions to ensure that nitrogen leaching does not lead to significant impacts. In the case of Brazil, indicative externalities have been calculated for the BIG/CC and reference systems based on pollutant-specific externality values calculated for Europe, to provide an indication of the magnitude of the externalities of the systems and provide a basis for their comparison.

The assessment of the externalities of atmospheric emissions of regulated pollutants shows that they are of the same order of magnitude as the internal costs of the fuel cycles. However, they vary considerably depending on the fuel cycle and location. The externalities of the BIG/CC fuel cycles are generally significantly lower compared to those of the reference fuel cycles. Only for the UK case study, the externalities of CCGT electricity are similar to those of electricity from BIG/CC. However, if the same plants are located in Lauffen, the difference in externalities increases significantly. The difference would be even greater if emissions from biomass production and transport could be reduced.

Externality estimates are strongly site-specific, with large increases in the values calculated for the case studies between the original sites and the Lauffen reference site in Germany. The difference is mainly due to the exposure of a larger population for plants sited at the German site. While the ratio between the externalities of the biomass and fossil fuel cycles is constant for different sites, the difference between their externalities increases with the externality. The net benefit of biomass use appears then more important for sites which result in greater environmental impacts.

A damage cost range associated with CO_2 emissions has been considered to provide an indication of CO_2-related externalities. Based on the calculations performed, the externalities associated with CO_2 emissions are likely to be similar in magnitude to those associated with regulated pollutants. However, a greater uncertainty surrounds the externalities of CO_2. Future commercial BIG/CC systems can avoid CO_2 emissions from reference fuel cycles at little or no additional private cost, and with likely net social benefits, for co-generation applications. An assessment of the avoidance costs of CO_2 emissions in the case of electricity only applications in the UK shows that CO_2 emissions from coal electricity can also be avoided at little additional private cost or even with a net social benefit if the other externalities are considered. The avoidance of CO_2 emissions by substituting BIG/CC electricity for CCGT electricity incurs a much higher cost and would be justifiable for damage costs generally higher than those considered in the damage cost calculations above. BIG/CC systems appear generally as an economically viable solution in the quest for reduced social costs of energy supply.

As BIG/CC systems begin to penetrate the market, their costs will be reduced and they will become more competitive with conventional energy sources, in particular in decentralised generation and co-generation applications. However, current costs of the BIG/CC fuel cycles are high, and the assessment of the economic benefits which can derive from their development is an important argument which could influence policy-making and corporate decision-making.

Certainly, the external benefits of BIG/CC systems compared to the reference systems, in particular coal based, provide a strong economic incentive for their introduction. In the case of coal large benefits can be obtained by the reduction of regulated pollutants and greenhouse gas emissions. In the case of natural gas most benefits will be associated with greenhouse gas emissions, depending very much on the cost associated with them. Though, depending on the location, significant benefits may also result from reduced regulated pollutants.

For example, assuming that externalities did not vary much with location in the UK, a realisation of the lower biomass energy potential from forest residues and energy crops using BIG/CC systems could replace about 7 TWh of coal electricity. This could save about €160 million in terms of environmental damages associated with regulated pollutants per year.

10 Fuel cycle sustainability

So far we have analysed the economic and environmental characteristics of the biomass fuel cycles, as well as discussed and, where possible, assessed the significant fuel cycle externalities. These are key factors in decision and policy making. They are also fundamental with regard to the sustainability of the fuel cycles. This section discusses the fuel cycles, biomass in particular, considered in this study in relation to the key aspects of sustainable development introduced in Chapter 2. An assessment of the sustainability of biomass fuel cycles is important as sustainable development is increasingly on the agenda of policy-makers worldwide.

Biomass is a promising contributor to the economic, environmental and social dimensions of sustainable development, in particular in terms of sustainable energy supply. It is a widespread resource that, if exploited with technically and economically viable technologies, can play an important role in economic development. It is a source of renewable energy which can contribute significantly to the rational use of natural resources, provided sustainable biomass resources are used. Furthermore, a proper exploitation of biomass energy can help preserve the environment, for example, through reduced emissions of atmospheric pollutants compared to conventional power sources. Also, biomass energy can enhance societal well-being through rural development and a more equitable distribution of resources.

Biomass can provide energy at a low social cost, a fundamental aspect of sustainable energy supply and a key requirement for economic development. Furthermore, biomass energy can result in significant economic benefits in terms of reduced expenditure associated with energy imports and enhanced energy security, in particular for developing countries.

Biomass can also provide an energy source compatible with environmentally sustainable development. The benefits of biomass fuel cycles in terms of atmospheric emissions can be considerable compared to fossil fuel cycles. The sustainability of biomass production, however, requires careful consideration. The renewable nature of the biomass resource needs to be ensured, and any negative impacts which could result from its procurement need to be avoided or minimised.

Greatest concern is often expressed with regard to the sustainability of SRC and its compatibility with sustainable agriculture, especially in relation to the application of inorganic fertilisers, herbicides and pesticides, and the effects of extensive monocultures. The main consequences would be on soil quality, water quality and use, biodiversity and human health. The discussion of SRC in the context of the UK case study indicates that the sustainable cultivation of SRC is possible. The input of inorganic fertilisers may not be required, and use can be made of organic fertilisers such as sewage sludge, although their application must be carefully controlled to avoid impacts, for example associated with nitrogen leaching. Pesticide application can be minimised through monitoring of the plantations and integrated pest management techniques. Herbicide application may be the most significant artificial input to SRC cultivation. However, the application of herbicide, which occurs early in the establishment phase of the plantation, should not result in significant impacts. In particular, herbicide application may be significantly lower over the lifetime of the plantation compared to alternative land uses e.g. arable crops. Also, sustainable SRC schemes will need to be carefully sited in order to avoid any negative impacts which could result from water use. The impact of SRC on biodiversity will largely depend on how the crop is managed and on the land use it displaces. It is possible that properly managed plantations will foster biodiversity. Decentralised BIG/CC plants need not result in extensive monocultures. Relatively small land areas are likely to be required and different SRC species can be planted to avoid the agronomic and visual impacts which characterise monocultures.

The use of forestry and sugarcane residues is not likely to result in environmentally unsustainable practices provided that some elementary precautions are taken. Actually, some benefits may result as discussed for the Swedish and Brazilian case studies e.g. reduced acidification and nitrogen leaching in Swedish forest. Issues associated with the extensive use of managed forests for timber and of extensive sugarcane plantations are considered to be outside the scope of this study. These are issues which need to be addressed separately and which may have a consequence on the forestry and sugarcane resources available in the future.

Biomass energy could bring about significant social benefits in terms of job creation, capacity building, poverty alleviation and rural development in general.

The assessment of the sustainability of the biomass fuel cycles considered can be addressed in more detail through the discussion of a series of monetary and non-monetary indicators. Social costs are considered to provide a measure of sustainability, albeit not a sufficient one to ensure its attainment. Previous chapters have estimated the private costs of energy from BIG/CC systems and compared them to the costs of energy from conventional, mostly fossil, systems. This chapter has provided an indication of the externalities which may be associated with the biomass fuel cycles considered, and compared these with estimates of external costs from reference systems including fossil fuel cycles.

The competitiveness of BIG/CC systems in the longer term is likely to improve, provided that suitable market introduction strategies are in place. Where forestry and sugarcane residues are used, reductions in costs are likely to be mainly due to reductions in the cost of the installation and to some extent due to reductions in the costs of collecting and transporting the fuel. Where SRC is used, significant cost reductions may result from reductions in the cost of the biomass fuel.

In the case of BIG/CC co-generation plants producing electricity and district heat in Sweden it appears that the cost of energy produced can be brought to be competitive with that of coal fuelled fluidised bed combustion co-generation plants. The cost of energy is found to be significantly higher for early commercial gasification-based biomass electricity compared to electricity from coal or gas in the UK. Only for the larger BIG/CC systems considered (c. $60MW_e$), the cost of electricity approaches that of electricity from coal. The estimation of the electricity costs from BIG/CC systems fuelled with sugarcane residues in Brazil indicates that surplus electricity can be generated at sugarcane processing plants at a cost competitive with marginal cost estimates for electricity generation in Brazil.

The consideration of the externalities leads to a more cost competitive position of the BIG/CC systems relative to the reference systems, especially if external costs associated with CO_2 emissions are considered.

The biomass fuel cycles considered generally result in much lower externalities compared to the reference systems, reflecting their significantly lower environmental impact. In some cases the biomass fuel cycles may even result in external benefits, as is the case of the Swedish biomass case study where the biomass fuel cycle results in reduced acidification. Furthermore, biomass fuel cycles are likely to result in benefits to the national economy, though to a varying extent depending on the particular biomass fuel cycle and on the displaced reference system. The competitiveness of BIG/CC systems relative to conventional energy sources is significantly affected by the externalities associated with regulated pollutant, but it will strongly depend on the private cost reductions and on the weight attributed to greenhouse gas emissions in the future.

A comparison of social costs indicates that BIG/CC systems have a role to play in a more sustainable energy supply. However, social costs do not guarantee emissions below critical levels, the gradual and timely substitution of non-renewable sources and the contribution of energy to social sustainability. A strong sustainability stance aimed at preserving the ecosystem, promoting an efficient use of non-renewable resources and their substitution by renewable resources, and improving social conditions strengthens the position of biomass.

Issues of acidification, tropospheric ozone, eutrophication and particulate formation associated with SO_2 and NO_x emissions are far from being solved, as illustrated for example by the recent European Union national emissions ceilings directive (CEC, 1999). Legislation limiting emissions from power generation is likely only to have a limited effect and more drastic measures and switches to cleaner sources are required to reduce the impacts related to SO_2 and NO_x and particulate emissions. Governments are also recognising the threat to the environment resulting from climate change and gradually committing to reducing CO_2 emissions. The European Union is committed to reduce CO_2 equivalent emissions by 8% by 2012 compared to 1990 levels. The proposed reduction will require a greater share of renewable energy supply, biomass in particular. Non-renewable fuels are under considerable pressure for stationary and mobile power generation, and the pressure on these resources will increase as the demand for energy increases worldwide. In particular, the pressure on cleaner, cost-effective conventional fuels, i.e. natural gas, is likely to increase considerably. Most energy scenarios predict a more significant reliance on renewable energy to satisfy future energy supply, and BIG/CC systems provide a clean, efficient and large renewable energy source.

The social sphere is a fundamental component of sustainable development, and biomass energy systems, BIG/CC systems in particular, are likely to present social benefits compared to conventional power supply. Benefits arise mainly from the reliance on local resources and the contribution to rural development.

BIG/CC systems appear as a promising contributor to a more economically, environmentally and socially sustainable energy supply. The sustainable features of biomass systems, BIG/CC systems in particular, are likely to be an integral feature of future energy policy. The introduction of cleaner energy sources, the substitution of non-renewable energy by renewable energy sources, the promotion of energy sources which can benefit less favoured parts of society and lead to social gains should all be objectives of a policy aimed at a more sustainable energy supply.

CHAPTER 9

CONCLUSION

1 Introduction

An analytical framework has been developed for assessing the energy potential and economic and environmental performance of gasification-based biomass fuel cycles at a regional level, and for their comparison with selected conventional reference systems. Three region-specific case studies are analysed, based on circulating fluidised bed gasification coupled with a combined gas and steam turbine cycle and characterised by different biomass fuels (forestry residues, SRC and sugarcane residues). The analysis includes a discussion of the regional context and biomass potential, a description of the fuel cycles and discussion of related technical issues and priority impacts, a resource use, costs, emissions and employment inventory, and a discussion of the external costs and benefits and sustainability of the fuel cycles. It provides key economic and environmental parameters in support of decision and policy-making. Based on its results, it appears that the biomass fuel cycles considered represent an important sustainable energy source. The following sections summarise the main findings of the study and discuss the future of BIG/CC systems.

2 Biomass fuels

There is a large energy potential associated with the biomass fuels considered, as summarised in Table 56. The ranges for the potential estimates are an indication of the uncertainty over the potentials that can be achieved in practice. They depend much on agricultural policy, forestry conservation measures and accessibility to the resource in the case of sugarcane harvest residues. The production of the fuels does not present any significant technical barriers and can currently be achieved at reasonable cost and in an environmentally sound manner.

Table 56: Biomass energy potential in selected regions [TWh]

	Energy potential [TWh]
Sweden	
Forest fuel[1]	15 - 165
Energy crops[2]	15 - 60
UK	
Forest fuel[3]	6 - 9
Energy crops[4]	10 - 140
Brazil	
Bagasse[5]	227
Cane harvest residues[6]	58 - 160

[1] Börjesson et al. (1997) and Jörgensen et al. (1998)
[2] Börjesson et al. (1997)
[3] DTI (1999)
[4] low value: 5% of arable land; high value: 10% of agricultural land
[5] based on 1996/7 Brazilian sugarcane harvest
[6] based on 1996/7 Brazilian sugarcane harvest; low value: 25% recovery; high value: 75% recovery. Note: it is estimated that 0.248 kWh of electricity can be exported from cane mills per kWh of energy in the form of cane residues supplied to a BIG/CC plant

The production and transport of the biomass fuels exhibit different levels of commercial readiness. The production of wood chips from forestry residues is well developed in Sweden as a result of the considerable experience acquired with wood chip use in district heating. Equipment and logistics for the production and transport of wood chips from SRC are being demonstrated, and significant experience is being gained from the ARBRE fuel cycle. Equipment and activities related to the collection and transport of sugarcane harvest residues require most development, though significant experience is being gained through field trials using conventional agricultural equipment.

A detailed cost calculation shows that the biomass fuels can currently be delivered to the plant at a low cost, as shown in Table 57. Based on the results of a sensitivity analysis, it is estimated that a 10% to 20% cost reduction could be achieved in the short-term. Reductions in costs are likely to result from increases in SRC yields and reductions in machinery and transport costs as the biomass industry develops.

Table 57: Biomass fuel costs [€/GJ]

	Production cost [€/GJ]	Cost delivered at plant [€/GJ]
Sweden		
Forest fuel	2.12	2.97
UK		
Forest fuel	2.10	3.18
Energy crops	2.00	2.32
Brazil		
Cane harvest residues	1.17	1.39

Note: costs based on calculations for Värnamo plant in Sweden, ARBRE plant in UK and average sized mill in Brazil; 5% discount rate for Sweden and UK and 10% discount rate for Brazil; sensitivity of costs to different parameters can be seen in Section 2.7 of Chapter 5 and in Section 2.2 of Chapter 7

The environmental analysis of biomass fuel production does not reveal any major insurmountable environmental concerns. Forestry residues and sugarcane harvest residues are a result of other activities and their collection and transport is not expected to raise major environmental concerns if good practice is followed. In particular, the amount of residues to be left in the field need careful consideration. SRC is found to affect a wider range of environmental issues e.g. soil quality, water use and quality, biodiversity and rural amenity, the main concerns being associated with water use and quality. However, significant impacts can be avoided given suitable precautions are taken in the application of fertilisers and in the in siting of the plantations. Good practice guidelines are available (ETSU, 1996; ARBRE, 1996b and Ledin and Alriksson, 1992) which provide advice on how to grow SRC in an environmentally sound manner. Emissions from the machinery used in the production and transport activities are likely to result in significant environmental impacts, based on current engine technology and fossil fuel use. These emissions contribute significantly to the biomass fuel cycle emissions. Amenity issues, such as visual impacts, noise and odours, should not be neglected however trivial or difficult to value in monetary terms they appear, as they may be a major cause of public opposition

The energy analysis shows that biomass fuels can be produced with very low non-renewable energy requirements. For the case studies considered, the renewable energy content of the biomass delivered to the plant is more than 50 times the non-renewable energy input to the process.

3 Energy from biomass

Biomass gasification coupled with combined cycle gas and steam turbines offers the potential for high electrical efficiency, well above the 32% assumed to characterise the demonstration plants. Efficiencies are projected to range between 43% and 53% for electricity only systems, depending on gasifier operating pressure and plant capacity. High electrical conversion efficiencies are of great importance for decentralised biomass systems to be able to compete with conventional energy sources.

Biomass gasification and the use of biomass-derived syngas in gas turbines do not present major technical barriers, and the Värnamo plant has demonstrated that high-pressure gasification can be successfully coupled with gas turbine operation. However, the reliable operation of such systems still needs to address technical issues such as feeding blockages. Also, although the syngas quality has proven to be suitable for combustion in gas turbines, longer operating times on syngas are desired to assess the reliability of operation and lifetime of the equipment. The ARBRE plant, currently under construction, will be the first plant to demonstrate a BIG/CC system based on low-pressure gasification. Very little experience exists on the gasification of sugarcane residues. These may present additional difficulties because of the low density of the fuel which may affect the feeding system, the presence of syngas contaminants leading to turbine corrosion problems and the presence of silica and potassium in the ash leading to low ash melting points. Preliminary tests with sugarcane residues have shown promising results, but more extensive testing is required to solve any technical difficulties and prove the reliable gasification of sugarcane residues.

The costs of BIG/CC systems are currently high because of the early commercialisation stage of many of the plant components and the demonstration nature of the integrated system. It is estimated that significant cost reductions could be obtained through economies of scale and replication. Table 58 compares the estimated capital cost of the demonstration plants with the capital cost of early commercial plants of 30 MW_e capacity. At scales deemed suitable for commercial plants, it is likely that the capital costs of low-pressure and high-pressure systems will be similar.

Table 58: Capital cost of BIG/CC systems [€/kW$_e$]

	Capital cost [€/kW$_e$]	
	Demonstration	*Early commercial*
HP-BIG/CC	4,700	1,400 - 1,750
LP-BIG/CC	3,900	1,400 - 1,750

Note: see Section 2.7 of Chapter 5 and Annex 1 for details

The pre-treatment of the biomass fuel, gasification and syngas cleaning activities should not entail any significant environmental burdens. Precautions need to be taken, however, with regard to emissions of dust and volatile hydrocarbons to the air (or water if the gas emitted from the drying process is condensed) from the drying of the fuel. The water effluent from wet gas scrubbing in the case of atmospheric gasification systems should not be of environmental concern since the biomass fuels considered are not likely to contain significant amounts of contaminants e.g. heavy metals and tars. The ash produced should not contain any significant amount of contaminants and can be recycled back to the fields. The most significant environmental burden is the emissions from the combustion of the syngas in the gas turbine.

Emissions from BIG/CC systems compare favourably with those from conventional systems fuelled with biomass, natural gas and coal. Emissions of the main regulated pollutants are generally much lower for a BIG/CC system compared to a coal combustion system, and also compared to a biomass combustion system. The benefits are reduced when comparing BIG/CC to natural gas-fuelled combined cycle plants, although significant reductions in NO_x emissions can be achieved. The conversion of renewable biomass does not contribute net CO_2 emissions to the atmosphere. Hence, its use can significantly reduce CO_2 emissions associated with conventional electricity and heat production.

For example, the realisation of the lower biomass energy potential from forest residues and energy crops in the UK using BIG/CC systems could replace about 7 TWh of coal electricity. This could reduce NO_x emissions by about 12,400 t/yr, SO_2 emissions by about 7,300 t/yr, PM emissions by about 1,100 t/yr and CO_2 emissions by about 6,900 t/yr. Other emissions of pollutants, such as heavy metals, would also be reduced. However, CO emission may increase by about 5,000 t/yr.

The energy analysis shows that the energy output from a Värnamo type co-generation plant is about 13 times the non-renewable energy input to the full fuel cycle. For an

ARBRE type electricity plant the output is about 8 times the non-renewable energy input to the full fuel cycle. For a gasification-based co-generation plant installed at an average size Brazilian sugarcane mill the energy output is about 19 times the non-renewable energy input to the full fuel cycle.

4 Total costs and benefits of BIG/CC and competing systems

The extensive testing of biomass fuels in integrated gasifier-gas turbine demonstration facilities will prove the technical viability of the systems and lead to their improvement. Also, increasing demand for biomass fuels will lead to improvements in the equipment and logistics used for their production and transport. Experience with BIG/CC systems and their scale-up will lead to reductions in costs across the fuel cycle.

The cost of energy calculated based on the demonstration projects is high, but there is considerable scope for achieving a more competitive cost. Table 59 compares the cost of energy from BIG/CC demonstration plants with those of future early commercial BIG/CC systems (30 MW_e) and with the cost of energy from conventional sources.

Table 59: Cost of energy from BIG/CC and competing systems [m€/kWh]

	BIG/CC demonstration	BIG/CC early commercial[1]	Conventional energy
Sweden[2]	53	18 - 30	25 - 38
UK[3]	80	40 - 65	CCGT: 24-28; Coal: 34-44
Brazil		26 – 40[4]	27 – 34[5]

[1] 30 MW_e capacity; low value: 5% discount rate; high value: 15% discount rate
[2] co-generation plant: costs are allocated on energy basis; reference system: CFB coal combustion
[3] electricity only plant
[4] co-generation plant: costs are allocated on energy basis; see Section 2.3 of Chapter 7 for cost variations according to allocation basis; costs refer to first commercial plants at average size cane mills and do not account for reductions in costs associated with replication – it is expected that replication could reduce costs of energy by about 20%
[5] emphasis in Brazilian case is on exports of surplus electricity so comparison is made with CCGT electricity costs

The costs in Table 59 show that significant reductions can be achieved in the cost of energy from BIG/CC systems. In applications where BIG/CC systems are used for co-generation, energy may be produced at a cost competitive with that of energy from conventional sources. This is the case for Sweden where the conventional system is a circulating fluidised bed coal combustion plant. In the case of Brazil, it is assumed that surplus electricity from BIG/CC systems sited at sugarcane processing plants will have to compete with electricity from CCGT plants fuelled with natural gas. The competitiveness of biomass electricity will depend on cost allocation, and the costs calculated indicate that electricity from sugarcane may be close to being competitive. In the case of the UK, where the BIG/CC plants are assumed to produce electricity only and compete with large-scale coal and natural gas plants, the cost of electricity from BIG/CC systems is likely to be higher compared to the cost of electricity from conventional sources, CCGT electricity in particular. The decentralised nature of BIG/CC systems should result in economic benefits compared to electricity from centralised plants, which should be accounted for in the assessment of the cost of energy to the consumer.

Conventional fossil-based energy systems are likely to have a greater impact on the environment, mainly associated with emissions from the conversion stage. An attempt at the monetary valuation of the environmental impacts associated with the main regulated pollutants (NO_x, SO_2 and PM) and the consideration of CO_2 damage costs provided in the literature shows that they have a significant influence on the actual costs of energy generation. Table 60 shows the externalities associated with regulated pollutant emissions and with CO_2 emissions.

Table 60: Externalities associated with the BIG/CC and reference systems [m€/kWh]

	BIG/CC	Reference[2]
Sweden (Värnamo)	1.5 (0.18 – 0.5)	5.8 – 7.2 (6.5 – 20)
UK (Eggborough)	6.0 (1.2 – 3.2)	7.3 – 29 (16 – 44)
Brazil[1]	0.46 – 2.8 (0.012 – 0.034)	1.5 – 9.2 (3.2 – 9.0)

Note: values in parentheses provide an estimate of CO_2 damage costs
[1] the range for the externalities of regulated pollutants is based on pollutant-specific externalities for Europe
[2] the ranges cover the externality values for the different reference fuel cycles considered; for details refer to Sections 4-7 of Chapter 8

Large benefits can be obtained by replacing conventional fossil-based energy systems with BIG/CC systems. For example, assuming that externalities did not vary much with location in the UK, a realisation of the lower biomass energy potential from forest residues and energy crops using BIG/CC systems could replace about 7 TWh of coal electricity. This could save about €160 million per year in terms of environmental damages associated with regulated pollutants (NO_x, SO_2 and PM).

Emission location affects the externalities of local and regional pollutants, as discussed in Sections 4 and 5 of Chapter 8. Locations which result in higher externalities, e.g Lauffen in Germany, lead to an increased net benefit for biomass energy.

The environmental benefits which can result from the introduction of BIG/CC systems should act as an incentive for their development. Furthermore, a comparison of the cost of energy from future early commercial BIG/CC systems and conventional fossil fuel-based systems indicates that reductions in emissions can be achieved at little or no additional private cost, and at a net social benefit. This is particularly the case for co-generation applications and when substituting coal for electricity only generation. This is also reflected in the CO_2 avoidance costs estimated in Table 61. The cost of avoiding emissions, mainly CO_2, by substituting CCGT electricity is significantly higher (Table 61). However, the avoidance costs for CO_2 are still within the range typical of damage costs cited in the literature (IPCC, 1996).

The comparison of the cost of energy based on social costs strengthens the position of BIG/CC systems considerably, in particular if the potential costs of climate change are considered. CO_2 emissions can be generally avoided at low cost by substituting conventional fossil energy sources by BIG/CC systems.

Table 61: Avoidance cost of CO_2 emissions based on electricity generation from BIG/CC fuelled with SRC compared to coal and natural gas [€/tCO_2]

Reference fuel cycle	Avoidance cost (excluding externalities*)		Avoidance cost[1] (including externalities*)	
	30 MW_e BIG/CC	60 MW_e BIG/CC	30 MW_e BIG/CC	60 MW_e BIG/CC
UK coal	6.4 - 21.9	0.3 - 9.6	-17.0 - (-1.6)	-23.2 - (-13.9)
UK gas	48.5 - 111	30.5 - 75.8	44.6 - 107	26.6 - 71.9

Note: the low avoidance cost values relate to a low discount rate (5%) and the high avoidance cost values relate to a high discount rate (15%)

* the externalities considered here are those estimated for NO_x, SO_2 and PM using the EcoSense model

1 it should be noted that the case for biomass would be strengthened for plants sited at locations resulting in higher externalities from regulated pollutants e.g. Lauffen site; see Sections 4 and 5 of Chapter 8

The analysis has attempted to discuss and quantify what are believed to be the most significant externalities. However, the assessment of the externalities is by no means exhaustive, and the external benefits of BIG/CC systems compared to conventional energy sources may be greater than those illustrated here (although emissions such as CO deserve further study). Fossil fuels, coal in particular, may emit other polluting agents e.g. heavy metals, which have not been considered here, and the upstream impacts of fossil fuel cycles should receive greater attention. Energy crops, SRC in particular, may present benefits which should be accounted for in promoting their development e.g. shelter against wind erosion, prevention of water erosion, buffer against nitrogen leaching from agricultural practices. Biomass production can then contribute to more sustainable agricultural practices. Also, biomass energy systems present a variety of socio-economic benefits associated with enhanced energy security, reduced expenditure on fuel imports and job creation.

5 Sustainability

Biomass energy systems, BIG/CC systems in particular, have the potential to contribute to the economic, environmental and social dimensions of a sustainable energy supply. Energy can be produced at a cost similar to energy from conventional sources. This is particularly the case if environmental externalities are accounted for. The biomass energy systems considered can alleviate the pressure on the ecosystem compared to conventional fossil-based energy systems and the environmental impacts of biomass production are not likely to be significant if good practice is followed. In certain cases, biomass production may be accompanied by environmental benefits. Biomass can also contribute to inter- and intra-generational equity by reducing the exploitation of non-renewable resources, alleviating potentially long-term environmental impacts e.g. climate change, alleviating poverty through rural development and the creation of employment in economically disfavoured areas, and providing a widespread energy source which would reduce the dependency of many countries on imported fuels.

6 The future of BIG/CC systems

Although more efforts are required to demonstrate the technical and commercial viability of BIG/CC systems, they hold promise as a sustainable energy source based on biomass resource potential, projected cost reductions, and environmental and social benefits compared to conventional energy sources. BIG/CC systems provide a clean and efficient conversion technology for modern biomass use which can provide a significant contribution to future renewable energy supply. On these grounds it is believed that efforts should be dedicated to the demonstration and commercialisation of the technology.

Demonstration projects are aimed at proving the technical viability and reliable operation of BIG/CC systems. This involves the demonstration of a reliable and efficient biomass supply infrastructure, as well as reliable and efficient plant operation. The Värnamo plant has opened the path to BIG/CC plant demonstration, soon to be followed by the ARBRE plant which will also provide key experience with regard to the production and logistics of SRC. It is hoped that other plants will follow, building on the experience of the Värnamo and ARBRE plants and demonstrating the viability of systems in other application e.g. industrial co-generation, and using other fuels e.g. sugarcane residues.

Market penetration of BIG/CC systems will require commercial viability. The costs of the demonstration systems are high, but significant cost reductions can be achieved and are necessary if BIG/CC systems are to compete with conventional fossil-based systems. Cost reductions will require further support from government and could be stimulated through mechanisms similar to the UK NFFO.

The commercial viability of BIG/CC systems will depend on the cost at which they can deliver energy to the consumer compared to competing systems. It is imperative, in particular in a liberalised energy market, that regulations be in place that internalise the externalities of energy supply, and allow different energy sources to compete on a level playing field. Market introduction support is necessary to have the costs of BIG/CC systems converge towards those of conventional energy systems and bring early commercial plants to the market. Then, a proper regulatory framework, which accounts for the environmental and social benefits of clean renewable systems such as BIG/CC, is necessary to allow the early commercial systems to compete in the longer term.

Environmental and social benefits may be accounted for through taxes and subsidies based on actual environmental externality calculations such as those performed in this study or on standard price setting to achieve specific targets e.g. NO_x reductions. Tradable permit schemes associated with pollutants such as CO_2 and SO_2 could also benefit BIG/CC systems. Much will depend on the commitment to reducing emissions, on the costs which will be attributed to the emissions and the costs of alternative abatement and mitigation options.

Energy market structure will also affect the competitiveness of BIG/CC systems. The liberalisation of the energy market should stimulate competition in energy supply and lead to new players entering the market. This should lead to greater diversification in supply and to enhanced opportunities for decentralised generation and co-generation. A set of rules which guarantee the proper functioning of liberalised energy markets e.g.

rules and pricing structure governing access to the grid, are of great importance to the development of decentralised energy supply.

Commercial viability and a favourable market structure may, however, not be sufficient for the market penetration of BIG/CC systems. A variety of other factors such as the players involved and policies in related sectors e.g. agriculture, will have a strong influence. Information on the possibilities of biomass energy need to be directed to different players, be these farmers, the agro-industry, energy companies, financial institutions and local planning authorities. Biomass trade organisations can play a key role in terms of communication and strategies for implementing biomass energy projects. There is also a need to co-ordinate policies related to agriculture, energy and the environment which would allow to harness the cross-sectoral benefits of biomass energy.

The analysis presented in this study has investigated the issues, requirements and opportunities of BIG/CC systems. There remains much scope for further research in improving the performance and economics of BIG/CC systems. Also, further work is required in relation to technical and logistic issues regarding biomass production and supply and its environmental impacts. The environmental analysis could, for example, be extended to valuing the impact of other pollutants such as CO emissions; considering other atmospheric pollutants such as heavy metals; and assessing the potential benefits of SRC. Finally, more research is required into policies and strategies which could promote the development of gasification-based biomass fuel cycles.

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GLOSSARY

ASME:	American Society of Mechanical Engineers
atm:	Atmosphere
BIG/CC:	Biomass integrated gasification combined cycle
BoP:	Balance of plant
CFB:	Circulating fluidised bed
CFB/ST:	Circulating fluidised bed combustion coupled with steam turbine
CHP:	Combined heat and power
COE:	Cost of electricity
COH:	Cost of heat
DFA:	Damage function approach
EFI:	Ecosystem function indicator
EPI:	Environmental pressure indicator
ERF:	Exposure-response function
EU:	European Union
FB:	Fluidised bed
FCA:	Fuel-cycle analysis
FCI:	Fuel-cycle inventory
GDP:	Gross domestic product
HHV:	High heating value
HP-BIG/CC:	High-pressure biomass integrated gasification combined cycle
HRI:	Human resources indicator
HRSG:	Heat recovery steam generator
IEA:	International Energy Agency
IGCC:	Integrated gasification combined cycle
IPP:	Independent power producer
LCA:	Life-cycle analysis
LCPD:	Large Combustion Plant Directive
LCV:	Low calorific value
LP-BIG/CC:	Low-pressure biomass integrated gasification combined cycle

Modt:	Million oven dry tonnes
MSW:	Municipal solid waste
Mtoe:	Million tonnes of oil equivalent
NFFO:	Non fossil fuel obligation
NFU	National Farmers Union (UK)
Nm^3:	Normal cubic metre
NMHC:	Non-methane hydrocarbon
NVZ:	Nitrate vulnerable zone
O&M:	Operation and maintenance
OECD:	Organisation for Economic Co-operation and Development
odt:	Oven dry tonne
PAH:	Polyaromatic hydrocarbon
PF:	Pulverised fuel
PM:	Particulate matter
ppmv:	Parts per million by volume
ppmw:	Parts per million by weight
R$:	Brazilian Reais (currency)
R&D:	Research and development
RDF:	Refuse derived fuel
REC:	Regional electricity company
RUI:	Resource use indicator
SEK:	Swedish Krona (currency)
SRC:	Short rotation coppice
tC:	Tonne of carbon
tc:	Tonne of cane stalk
VAT:	Value added tax
VLYL:	Values of life years lost
VOC:	Volatile organic compound
VOSL:	Value of a statistical life
yr:	Year
€:	EURO (currency)
£:	British Pound (currency)

ANNEX 1

FUEL CYCLE INVENTORY DATABASE AND MODEL

1 Purpose of the database and model

The present annex describes a database and model for calculating the non-renewable energy, private costs, employment and emissions inventories of gasification-based biomass fuel cycles and conventional fuel cycles. The integrated approach is innovative with regard to its detailed analysis of significant energy-economy-environment impacts of gasification-based biomass fuel cycles. It provides the basis for assessing the social costs and benefits as well as sustainability of the fuel cycles. The inclusion of conventional energy systems allows for a transparent and understandable comparison of gasification-based biomass and conventional energy systems. The database and model structure is designed to be flexible and modular, and fuel cycle activities and data can be easily modified or added. A schematic representation of the spreadsheet-based database and model is shown in Figure 5 of Chapter 2.

2 General structure of the database and model

The model calculates the fuel cycles' inventories based on four fundamental fuel cycle stages (i.e. production, transport, conversion and waste disposal or recycling) and their activities. Detailed information is provided on the activities involved, specifying the equipment used and its power output, the work period and personnel required, and the materials consumed. In order to perform the calculations, the information on the activities must be backed by a basic set of data on the characteristics of biomass and other materials, costs, emissions and labour. The information on the conventional fuel cycles is less detailed and provided with a greater level of aggregation. For example, aggregate emissions and labour requirements are provided for the fossil fuel cycle stages up to the conversion stage and for the conversion stage. Costs and energy balance figures refer to the full fuel cycle.

The database contains data on:

- the characteristics (e.g. calorific value, moisture content, elemental composition) of energy crops (e.g. short rotation willow and poplar coppice), forestry residues (e.g. pine and spruce fellings), agricultural residues (e.g. sugarcane residues), and possibly other site specific resources;
- the characteristics (e.g. mass, power, lifetime, specific fuel consumption) of the machinery used in biomass production and transport;
- the cost of fuels, materials (e.g. twine), machinery and labour employed in biomass fuel cycles for different countries (i.e. Sweden, UK, Brazil);
- the energy content of fuels, materials and machinery (the latter derived from the material composition of machinery, the energy embodied in the materials used and the fabrication energy) used in biomass fuel cycles;
- the specific atmospheric emissions associated with equipment used in biomass fuel cycles;
- emissions associated with fossil fuel cycle stages up to the conversion stage and for the conversion stage;
- fossil fuel costs and investment and operation and maintenance (O&M) costs for fossil fuel plants;
- labour associated with fossil fuel cycle stages up to the conversion stage and for the conversion stage;
- full fuel cycle energy balances for fossil fuel cycles.

The following additional data are derived within the database:

- specific fuel consumption by different biomass production activities (e.g. collection, chipping and forwarding in the case of biomass production from forestry residues) based on assumptions on the power developed by the machinery used in different activities;
- hourly discounted capital cost of machinery use based on assumed annual operation time, residual value and discount rate.

The fuel cycle inventory calculations require the definition of fuel cycle scenarios containing information on:

- regional and biomass fuel characteristics (i.e. moisture content, ash content, yield, percentage land use, recoverable residues);
- biomass fuel mix and transport capacity and distances (when the latter is not calculated using the biomass yield, recoverability and land use);
- biomass conversion plant characteristics (i.e. capacity, lifetime, efficiency, annual operating time) (these may be derived values, as in the Brazilian case study where they are derived based on the sugarcane processing plant capacity);
- waste disposal or recycling option (i.e. transport distance for landfill or recycling, landfill tipping fee or cost of processing ash for recycling);
- reference system characteristics (i.e. conventional fuel cycles involved, share of total energy generated, capacity, lifetime, efficiency, annual operating time).

The following calculations are performed based on the scenarios defined:

- general scenario information: energy input as biomass, feedstock weight and volume, biomass truckloads and transport distance[14], diesel consumption, plant capacity and annual operating time[14], energy output as heat and electricity, and displaced fossil fuel consumption;
- machinery use, materials use, and total work period (labour requirement) associated with biomass production and transport;
- biomass fuel costs: annualised biomass production cost (including breakdown into investment and O&M - labour, fuel, materials), biomass transport cost, and total biomass cost at plant gate;
- biomass conversion cost: annualised investment cost and O&M costs;
- cost of electricity and heat allocated on the basis of energy and exergy contents;
- biomass fuel cycle energy balance: energy requirement of activities associated with biomass production, transport and storage (direct: diesel consumption; indirect: energy embodied in materials and machinery), energy requirement of the biomass conversion plant (including indirect energy associated with plant construction), total energy requirement of the biomass fuel cycle, energy difference, energy ratio (associated with biomass fuel energy content and useful energy generated);

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[14] If derived value

- reference system energy balance;
- biomass fuel cycle atmospheric emissions inventory: emissions from biomass production and transport activities, emissions from the biomass conversion plant, total biomass fuel cycle emissions;
- reference system emissions inventory: emissions from fossil fuel extraction, processing and transport activities, emissions from reference conversion plant, and emissions from waste disposal activities;
- biomass and reference fuel cycle expenditure (necessary to perform input-output calculations).

The calculations provide the fuel cycle inventory data which is used for the economic and environmental analysis of the biomass and reference systems (see Chapters 5 and 7). The spreadsheet model also produces the tables and graphs used in the analysis. The fuel cycle inventory also provides a basis for other calculations such as the externalities associated with the fuel cycles. The expenditure calculations are used for estimating indirect emissions and employment using an input-output model (i.e. the EMI model). Furthermore, the fuel cycle inventory provides a basis for the discussion of the sustainability of the fuel cycles.

3 The database

3.1 Data relevant to biomass production and transport

3.1.1 Biomass types and characteristics

The database contains information on agricultural and forestry residues and on energy crops used in the study (Table 62).

Table 62: Biomass characteristics

Biomass type	Location	Lifetime [yrs]	Harvesting interval [yrs]	Yield [odt/ha/a]	Calorific value (wet) [GJ/t]	Moisture content [%]	Calorific value (dry) [GJ/odt]
SRC Poplar, Willow	UK	16	4	10	11	30	18
Forest residues Pine and Spruce	Sweden	-	80-120	1.2	11	30	18
Agricultural residues (Sugarcane residues)	Brazil	-	1	15	11	30	18

3.1.2 Machinery employed and its characteristics

Table 63 provides a list of technical specifications for the machinery employed in the production and transport of biomass. These specifications are required to calculate fuel consumption and energy embodied in the machinery. The lifetime is also needed to calculate the hourly cost of machinery use.

Table 63: Machinery characteristics (Source: Matthews et al., 1994; Börjesson, 1996; Nix, 1996; COPERSUCAR, 1997 and Braunbeck, 1998)

Machinery	Fabrication energy [MJ/kg]	Mass [kg]		Horsepower [hp]		Lifetime [h]	
		Low	*High*	*Low*	*High*	*Low*	*High*
SRC (UK)							
Tractor	11	1200	4000	100	150	10000	12000
Subsoiler	5.9	200	300	-	-	2500	5000
Plough	6.3	700	1200	-	-	2500	5000
Harrow	5.9	700	1400	-	-	2500	5000
Sprayer/broadcaster	5.1	300	500	-	-	2500	5000
Rotavator	5.9	1200	1400	-	-	2500	5000
Planter	5.1	550	600	-	-	2500	5000
Trailer	5.1	1200	2500	-	-	10000	12000
Brush cutter	11	8	10	2.5	3.5	2500	5000
Harvester (forage)	11	9000	12000	250	350	5000	10000
Harvester (bundle)	4.8	6000	9000	100	150	5000	10000
Chipper (bundle)	11	6000	7500	150	250	5000	10000
Forestry (Sweden, UK)							
Forwarder	11	2800	7500	100	150	10000	12000
Chipper (forestry)	11	6000	9000	400	500	5000	10000
Shuttle	11	2800	7500	100	150	10000	12000
Sugarcane (Brazil)							
Tractor	11	6000	6000	150	150	12000	12000
Trailer	5.1	7500	7500	-	-	12000	12000
Swather	4.8	1500	1500	150	150	12000	12000
Baler	4.8	7000	7000	150	150	12000	12000
Handler	11	4000	4000	150	150	12000	12000
General							
Truck	11	10000	10000	300	400	8000	13000

Specific fuel consumption for all diesel fuelled machinery is given as 0.1 - 0.15 l/hp h. Specific fuel consumption for the brush cutter is estimated at 0.4 – 0.6 l/hp h.

3.1.3 Fuel, material, machinery, labour and transport costs

Fossil fuel, materials, machinery, labour and transport costs shown in Table 64 to Table 68 are used to calculate the cost of biomass fuel. The coal and natural gas costs are used to calculate the cost of energy from fossil fuel cycles.

Table 64: Fossil fuel costs (Source: IEA, 1996)

Fuel	Cost		
	UK	*Sweden*	*Brazil*
Diesel [€/l]	0.56	0.54	0.33
Fuel oil [€/GJ]	2.40	2.33	-
Coal [€/GJ]	1.80	1.59	-
Natural gas [€/GJ]	2.15	-	-

Table 65: Material costs (Sources: Matthews et al., 1994; Grant et al., 1995; Nix, 1996 and Braunbeck, 1998)

Material	Cost	
	Min.	*Max.*
Agrochemicals (UK)		
Herbicide [€/ha]	21.7	29.0
Sewage sludge (4% solids) [€/t]	0	0
Other materials		
SRC cuttings (UK) [€/cutting]	0.06	0.12
Twine for baling [€/kg]	3.75	3.75
Waterproof protection [€/m^2]	6.75	6.75

Table 66: Machinery costs (Source: Nix, 1996; Jörgensen, 1997; CLAAS, 1997 and Braunbeck, 1998)

Machinery	Capital cost [€]
SRC (UK)	
Tractor	36197
Subsoiler	2413
Plough	4826
Harrow	3620
Sprayer/broadcaster	6033
Rotavator	7239
Planter	24132
Trailer	3620
Brush cutter	6033
Harvester (forage)	225000
Harvester (bundle)	112000
Chipper (bundle)	150000
Forestry (UK, Sweden)	
Forwarder	200000
Chipper (forestry)	300000
Shuttle	200000
Sugarcane (Brazil)	
Tractor	67278
Trailer	12798
Swather	15902
Baler	85627
Handler	48318

Hourly cost calculations for the machinery will be a function of annual operating time and discount rate. For SRC and forestry residues in the UK and Sweden annual operating times for different types of machinery are estimated to vary between 500 and 2000 hours. For sugarcane residues in Brazil, the farming machinery considered is assumed to operate for 3000 hours per year. Calculations are based on discount rates between 5% and 20%.

Table 67: Labour costs (including social charges) (Source: Nix, 1996; Jörgensen, 1997 and JornalCana, 1997)

Country	Sector	Cost [€/h]
United Kingdom	Agriculture/Forestry	7.5
Sweden	Agriculture/Forestry	9.6
Brazil	Agriculture	4.2

Table 68: Transport costs (Source: UK FTA, 1997; Sydkraft, 1997 and JornalCana, 1997)

Country	Cost [€/km]		
	Min.	*Max.*	*Mid-range*
United Kingdom	0.96	1.31	1.14
Sweden	1.13	1.70	1.42
Brazil	1.88	1.93	1.90

Note: Biomass transportation costs are based on contractor costs per unit distance travelled. Truck volumes are assumed to be $60m^3$ and $90m^3$ for the UK and Sweden, respectively. The load of a truck for sugarcane residue bales is assumed to range between 15 and 30t.

Other economic factors which are important in determining the cost of the biomass but which have so far not been considered are land rent, subsidies and risk and profit margins.

3.1.4 Energy embodied in fuels and materials

The energy content of the fossil fuels (Table 69) is provided in order to calculate the direct non-renewable energy input to the biomass fuel cycle. Also, the values for coal and natural gas are used to calculate fuel requirements and energy inputs of fossil fuel cycles.

Table 69: Energy content of fossil fuels (Source: Energy Data Conversion Handbook, 1984 and Matthews et al., 1994)

Fuel	Energy content
Diesel Oil [MJ/kg]	45.5
Petrol [MJ/kg]	46.9
Fuel Oil [MJ/kg]	42.7
Coal [MJ/kg]	23.6
Natural Gas [MJ/Nm^3]	35.2

Table 70 contains the energy embodied in a number of materials, whose use could have a significant effect on the energy balance of the biomass fuel cycle.

Table 70: Energy embodied in materials used (Source: Turhollow and Perlack, 1991; Kwant, 1993; Matthews et al., 1994; Worrell and Blok, 1994; Bhat et al., 1994; Grant et al., 1995; Nonhebel, 1995; Biewinga and van der Bijl, 1996 and Börjesson, 1996)

Materials in machinery			
Material	*Embodied energy (average)*		
Steel [MJ/kg]	24		
Cast iron [MJ/kg]	12		
Rubber [MJ/kg]	96		
Chemical inputs to agriculture			
Agrochemicals	*Embodied energy*		
	Low	*High*	*Mid-range*
Fertilisers			
Nitrogen [MJ/kg N]	38.6	88	63.3
Phosphate [MJ/kg P]	10.4	32.7	21.6
Potash [MJ/kg K]	8.0	11.6	9.8
Sewage sludge [MJ/kg]*	0	0	0
Herbicides [MJ/kg]	106	418	262
Pesticides [MJ/kg]	200	454	327
Other materials			
Material	*Embodied energy*		
	Low	*High*	*Mid-range*
SRC cuttings [MJ/cutting]	0.03	0.09	0.06
Waterproof protection			
Synthetic [MJ/kg]	47.3	47.3	47.3
Twine[MJ/kg]	60.7	60.7	60.7

* the energy content of sewage sludge is assumed to be nil because in the case considered (ARBRE Plant) no energy is specifically used or gained by its application as a fertiliser on SRC as opposed to other agricultural land.

The values provided for the energy embodied in materials used in machinery fabrication are taken from Börjesson (1996) and correspond to estimates for state-of-the-art industrial processes. The estimates for the specific energy requirement of chemical inputs into agriculture are obtained from a variety of sources, some of which provide estimates based on state-of-the-art industrial processes, while others date back to the 80's. The use of sewage sludge as an input to agriculture will be regarded as energy neutral because in the case study considered, if not applied to energy crops, the sludge will be used on other agricultural crops. Values for embodied energy are also provided for a number of other materials which could have a significant effect on the energy balance of the fuel cycle (e.g. cuttings, waterproof protection, twine).

3.1.5 Atmospheric emissions

Table 71 provides specific emissions for typical farming machinery. The values are based on Gover et al. (1996) and they show satisfactory agreement with other values encountered in the literature e.g. Börjesson and Gustavsson (1996).

Table 71: Emissions from farming machinery (Source: Gover et al., 1996)

Pollutant	Emission
NO_x [gNO_x/l diesel]	38.5
CO [gCO/l diesel]	15.5
NMHC [gNMHC/l diesel]	7.1
CO_2 [gCO_2/l diesel]	2466.2
PM [gPM/l diesel]	5.8
SO_2 [gSO_2/l diesel]	0.8

Biomass transport to the conversion plant is assumed to make use of trucks of different capacities. Table 72 provides typical values for emissions of air pollutants per unit distance travelled but independent of the load. Again these values are consistent with those provided by other sources e.g. Börjesson and Gustavsson (1996).

Table 72: Emissions from diesel fuelled heavy goods vehicle (Source: Gover et al., 1996)

Pollutant	Emission
NO_x [gNO_x/km]	13.1
CO [gCO/km]	3.9
NMHC [gNMHC/km]	0.45
CO_2 [gCO_2/km]	851.4
PM [gPM/km]	1.1
SO_2 [gSO_2/km]	0.3

Emissions of pollutants to the atmosphere from the production and transport of biomass are not only a result of the use of machinery. Agricultural practice, in particular through the use of agrochemicals, represents a possible source of airborne pollutants. Nitrous oxide (a powerful greenhouse gas) emissions result from the volatilisation of nitrogen fertilisers. Values found in the literature (see for example Gover et al., 1996) indicate that between 0.5 and 2% of N fertiliser is emitted as N_2O. However, greenhouse gas emissions from fertiliser application have not been considered as no inorganic fertilisers are assumed to be used in the UK case study and any application of inorganic fertilisers to forestry and sugarcane fields is assumed to lie outside the boundaries of the systems considered. Airborne pollutants arising from the spraying of herbicides or pesticides have also not been considered. Little is known on the possible impacts of these substances, but their impacts should not be significant if good practice is followed.

3.1.6 Activities inventory

Biomass production

The database contains an inventory of activities involved in the production of the biomass fuels (Table 73 to Table 75). Information is provided on the type of machinery used, the power developed by the machinery, the work period required to carry out a particular activity and the materials consumed by that activity. This data is necessary to assess the non-renewable energy use, costs, emissions and labour requirement of biomass production.

Table 73: Activities inventory for biomass fuel production from Short Rotation Coppice (Source: Matthews et al., 1994)

Activity	Machinery	Developed power [%]	Work period [h/ha]	Materials consumed
Herbicide treatment	Tractor (100-150hp), sprayer	60	0.2 - 0.6 (year 1, 2, 5)	0.10-0.15 l diesel/hp h 33 - 43 l act.ingr./ha (total application)
Subsoiling	Tractor (100-150hp), plough	70	1.3 - 1.8 (year 1)	0.10-0.15 l diesel/hp h
Ploughing	Tractor (100-150hp), plough	70	0.8 - 3.2 (year 1)	0.10-0.15 l diesel/hp h
Harrowing	Tractor (100-150hp), harrow	50	0.7 - 1.3 (year 1)	0.10-0.15 l diesel/hp h
Planting	Tractor (100-150hp), planter	40	1 - 8 (year 1)	0.10-0.15 l diesel/hp h 10000–15000 cuttings
Cutting back	Brush cutter	manual	14 - 28 (year 2)	
Fertilising	Tractor (100-150hp), broadcaster	40	0.2 - 0.5 (year 2, 5)	0.10-0.15 l diesel/hp h 7 dry t sewage/ha
Harvesting (bundle)	Harvester (100-150hp)	60	6 - 17.1 (year 4,7,10,13,16)	0.10-0.15 l diesel/hp h
Chipping (bundle)	Chipper (150-250hp)	50	10.2 (year 4,7,10,13,16)	0.10-0.15 l diesel/hp h
Rotovating	Tractor (100-150hp), rotovator	70	1.2 - 2.3 (year 16)	0.10-0.15 l diesel/hp h

Table 74: Activities inventory for biomass fuel production from forestry residues (Source: Mitchell and Hankin, 1993 and Jörgensen, 1997)

Activity	Machinery	Developed power [%]	Work period [h/t]	Materials consumed
Collection	Forwarder (100 - 150hp)	30	0.16 - 0.21	0.10-0.15 l diesel/hp h
Chipping	Chipper (150 - 250hp)	85	0.11 - 0.13	0.10-0.15 l diesel/hp h
Transfer	Shuttle (100 - 150hp)	60	0.11 - 0.13	0.10-0.15 l diesel/hp h

Table 75: Activities inventory for biomass fuel production from sugarcane harvest residues (Source: CLAAS, 1997 and Braunbeck, 1998)

Activity	Machinery	Developed power [%]	Work period [h/t]	Materials consumed
Windrowing	Tractor (150hp), swather	40	0.4	0.10-0.15 l diesel/hp h
Baling	Tractor (150hp), baler	60	0.6	0.10-0.15 l diesel/hp h
In-field transport	Tractor (150hp), trailer, handler (150hp)	50	1.25	0.10-0.15 l diesel/hp h

Biomass transport

Data on in-field transport and storage of biomass has been provided as part of the biomass production activities. Table 76 provides data on on-road transport activities. As in the case of the biomass production activities, the type of machinery used, the power developed by the machinery, the work period required (derived from assumptions on truck loads and average speeds) and the fuel consumed by that activity are specified. For sugarcane residue bales, handling activities are considered.

Table 76: Activities inventory for biomass transport

Activity	Machinery	Developed power [%]	Work period [h/t km]	Materials consumed
Transport	Truck (300 - 400hp)	45 - 65	0.0033 - 0.0067	0.10-0.15 l diesel/hp h
Loading/Unloading (straw)	Handler (150hp)	60	0.00067 - 0.0013	0.10-0.15 l diesel/hp h

3.2 Data relevant to biomass conversion

Emphasis is placed on gasification-based biomass conversion, although some data on combustion processes is also available to allow for comparison between the systems. Two types of generating systems considered: the low pressure biomass integrated gasification combined cycle (LP-BIG/CC) and the high pressure biomass integrated gasification combined cycle (HP-BIG/CC). The electrical efficiencies of the demonstration plants are 32% and the total co-generation efficiency for the Varnamo plant is 80%. Future electrical efficiencies for BIG/CC plants are estimated in Table 7 of Chapter 3.

3.2.1 Conversion costs

Investment costs for pieces of equipment for installations of particular capacities are derived from the literature. Curves have been fitted to the costs collected to enable the calculation of the costs of the equipment for installations of different capacities. Where unique values were available for certain pieces of equipment, scaling is achieved linearly or exponentially as suitable. Table 77 provides a series of formulae for the determination of the investment costs of different components of BIG/CC systems as a function of thermal capacity. The lifetime of a BIG/CC system is assumed to be 20 years.

Table 77: Biomass gasification combined cycle investment costs for different plant components

Component	**Cost**		**Comment**
	Low-pressure system	*High-pressure system*	
Fuel storage and handling			
Storage			Assumed part of civil works cost.
Conveyers	c_{conv}	same as low-pressure	Cost of 100m of modern design closed belt conveyers: 0.26 M€ [3].
Comminution	$Int(C_{th}/(C_{comm}*E_{wt}*d_{wt})+1)*c_{comm,ref}$	same as low-pressure	Roll crusher, capacity 50 m^3/h: 0.2 M€ [3]. $Int(C_{th}/C_{comm}(E_{wt},d_{wt})+1)$: number of crushers required based on biomass input.
Drying	$sqrt((E_{in,h}/E_{wt})/C_{dr,ref})*c_{dr,ref}$	same as low-pressure	18t/h rotary drum dryer: 3.5 M€ [3].
Gasification system			
Fuel feeding	$(E_{in,h}/E_{wt}/d_{wt})*c_{ff,ref}$	$(E_{in,h}/E_{wt}/d_{wt})*c_{ff,ref}$	Rotary valve screw feeder: 0.9 k€/m^3/h [3]. Screw piston feeder: 1.71 k€/m^3/h [3].
Air compressor	0	$(C_{th}/C_{th,ref})*c_{comp,ref}$	Linear, based on 0.5-0.75 M€ for 72 MW_{th} unit [2].
Gasifier	$sqrt(C_{th}/C_{th,ref})*c_{gas,ref}$	assumed to be same as low-pressure	Based on estimated volumes of lining and steel and scaling of a 72 MW_{th} unit. Cost of 72 MW_{th} gasifier unit: 1.4-2.3 M€ ($C_{th,ref}$= 72MW_{th})[1].

Tar cracker	same as gasifier	0	
Cyclones	$sqrt(C_{th}/C_{th,ref})*c_{cyc,ref}$	same as low-pressure	Scale-down (-up) of cyclones for 72 MW_{th} unit. Cost of cyclones for 72 MW_{th} unit: 0.9-1.9 M€ ($C_{th,ref}$= 72MW_{th}) [1].
Hot gas filter	0	$sqrt(C_{th}/C_{th,ref})*c_{hgf,ref}$	Scaling of cyclones for 151 MW_{th} unit. Cost of cyclones for 151 MW_{th} unit: 2.1 M€ ($C_{th,ref}$= 151MW_{th}) [2].
Gas cooling	$sqrt(C_{th}/C_{th,ref})*c_{gc,ref}$	same as low-pressure	Scaling of cyclones for 72 MW_{th} unit. Cost of cyclones for 151 MW_{th} unit: 2.1 M€ ($C_{th,ref}$= 72 MW_{th})[1].
Baghouse filter	$sqrt(C_{th}/C_{th,ref})*c_{bf,ref}$	same as low-pressure	Scaling of cyclones for 72 MW_{th} unit. Cost of cyclones for 72 MW_{th} unit: 1.2 M€ ($C_{th,ref}$= 72 MW_{th})[1].
Condensing scrubber	$sqrt(C_{th}/C_{th,ref})*c_{scrub,ref}$	0	Range for single or two-stage scrubber (two stage for removal of ammonia using water or H_2SO_4 acid). Cost of a scrubber for a 72 MW_{th} unit: 0.9-1.9 M€ ($C_{th,ref}$= 72 MW_{th}) [1].
Generation system			
Compressor	$(C_{th}/C_{th,ref})*c_{comp,ref}$	0	Linear scaling of compressor for 72 MW_{th} unit. Cost of a compressor for a 72 MW_{th} unit: 1-1.5 M€ ($C_{th,ref}$= 72MW_{th}) [2].
Gas turbine generator system	$1.0013*C_{gt}^{0.8094}$	same as low-pressure	Curve fit to costs provided for capacities between 5-40 MW_e[4].
Steam turbine generator system	$5.9455*C_{st}^{0.3269}$	same as low-pressure	Curve fit to costs provided for capacities between 5-40 MW_e[4].
Waste treatment			
Waste water treatment	$2.3845*ln(C_{el}) - 3.184$		Water from dryer and scrubber. Curve fit to costs provided for capacities between 5-60 MW_e [4].
System control			
System control	$c_{sc,ref}$	$2*c_{sc,ref}$	Depends on degree of automation and will affect operating costs. Cost of system control for 30 MW_e unit based on atmospheric gasifier: 2.3-4.7 M€ [1]. System control costs for pressurised system assumed to be twice those of LP system.
Electrical system			
Electrical system	5% of total investment	5% of total investment	

Design and installation			
Land, Buildings, Civil works	10% of total investment	8% of total investment	
Engineering	4% of total investment	4% of total investment	
Electricity connection (commissioning)	$0.0491*C_{el} + 0.0657$	$0.0491*C_{el} + 0.0657$	Curve fit to costs provided for plant capacities between 5-60 MW_e [4].

Legend:

C_{th}:	thermal capacity of conversion plant [MW_{th}]
t_s:	desired plant operating time on stored fuel [s]
E_{wt}:	energy content of wet biomass [MJ/t]
d_{wt}:	density of wet biomass [t/m^3]
c_{st}:	specific cost of storage facility [€/m^3]
c_{conv}:	cost of 100m of modern design closed belt conveyers [€]
C_{comm}:	comminution capacity [m^3/s]
c_{comm}:	cost of comminution equipment [€]
$E_{in,h}$:	hourly energy input to conversion plant [GJ/h]
$c_{dr,ref}$:	reference cost of drum dryer [€]
$C_{dr,ref}$:	reference drum dryer capacity [t/h]
$c_{ff,ref}$:	reference cost of 150m^3/h fuel feeder [€]
$C_{ff,ref}$:	reference fuel feeder capacity [m^3/h]
$C_{th,ref}$:	reference thermal capacity of gasifier [MW_{th}]
$c_{gas,ref}$:	reference cost of gasifier [€]
$c_{cyc,ref}$:	reference cost of cyclones [€]
$c_{hgf,ref}$:	reference cost of hot gas filter [€]
$c_{gc,ref}$:	reference cost of gas cooling tower[€]
$c_{bf,ref}$:	reference cost of baghouse filter [€]
$c_{scrub,ref}$:	reference cost of wet gas scrubber [€]
$c_{comp,ref}$:	reference cost of compressor [€]
C_{gt}:	generating capacity of gas turbine [MW_e]
C_{st}:	generating capacity of steam turbine [MW_e]
C_{el}:	electric capacity of conversion plant [MW_e]
$c_{sc,ref}$:	reference system control cost [€]

Source: Faaij et al., 1995[1]; Craig and Mann, 1996[2]; Piervik and Curvers, 1995[3] and Solantausta et al., 1996[4]

Table 78 provides a series of formulae for the determination of the operation and maintenance costs for BIG/CC systems as a function of thermal capacity.

Table 78: Operation and maintenance costs calculations for integrated gasification combined cycle systems (Source: Faaij et al., 1995[1]; Ståhl, 1997[2] and ARBRE, 1996a[3])

Category	Cost		Comment
	Low-pressure system	*High-pressure system*	
Fuel	$c_{bf}* E_{in,th}$	$c_{bf}* E_{in,th}$	The biomass cost, c_{bf}, is derived from the previously calculated biomass production and transportation costs.
Labour	$p*c_p$	same as atmospheric	5-20 employees at an average salary of €18750/yr.
Maintenance	2.5% of annualised investment	2.5% of annualised investment	
Utilities			
Electricity	0	0	No electricity imports.
Water	0	0	Neglected. Minimal water consumption due to recirculation.
Materials			
Sand	$c_{sand}*q_{sand}*E_{in,th}/E_{wt}$	0	0.0268 t sand/t wet fuel Cost of sand: 27.9 €/t [1].

Dolomite	$c_{Dol}*q_{Dol}*E_{in,th}/E_{wt}$	$c_{Dol}*q_{Dol}*E_{in,th}/E_{wt}$	0.0443 t/odt fuel [2]. Cost of dolomite: 27.9 €/t.
Sodium hydroxide (NaOH)	$c_{NaOH}*q_{NaOH}*E_{in,th}/E_{wt}$	0	0.138 kg/odt fuel Cost of NaOH: 1302 €/t [1].
Ammonium Sulphate	n.q.	0	Produced by scrubber.
Sulphuric Acid	n.q.	0	Produced by scrubber.
Fuel Oil	$C_{th}*t_{s-u}*c_{oil}$	$C_{th}*t_{s-u}*c_{oil}$	10h assumed for start-up.
Oxygen	$(O_{2,se}+O_{2,de})*c_{O2}$	$O_{2,de}*c_{O2}$	Scrubber effluent - BOD5: 200mg/l; COD: 450mg/l; 1000l/h; Domestic effluent - BOD5: 300mg/l; 80l/day person; 30 persons. Cost of oxygen: 0,47 €/kg $_{O2}$ [1,3]. Condensate from biomass drying not considered.
Ash disposal	$a*m_{bf}/b*(c_{transp}+c_{disp})$	$a*m_{bf}/b*(c_{transp}+c_{disp})$	Gasifier ash contains about 65% bed material and is composed of 35% bottom ash and 65% fly ash. Cost of ash disposal to landfill: 10-40 €/t.
Overheads	10% of annualised investment	10% of annualised investment	

Legend:

c_{bf}:	biomass cost [€/GJ]
$E_{in,th}$:	annual biomass input to plant [GJ]
p:	number of employees at plant
c_p:	average annual salary for plant employees [€]
c_{sand}:	cost of sand [€/t]
q_{sand}:	specific sand use [t of sand/t of biomass] (0.0268t of sand/t of biomass)
c_{Dol}:	cost of dolomite [€/t]
q_{Dol}:	specific dolomite use [t of dolomite/t of biomass]
c_{NaOH}:	cost of sodium hydroxide [€/t]
q_{NaOH}:	specific NaOH use [t of NaOH/t of biomass]
t_{s-u}:	start-up time [h]
c_{oil}:	cost of fuel oil [€/MWh]
$O_{2,se}$:	annual oxygen requirement for treatment of scrubber effluent [kg]
$O_{2,de}$:	annual oxygen requirement for treatment of domestic effluent [kg]
c_{O2}:	cost of oxygen [€/kg]
a:	ash fraction of biomass
b:	fraction of bed material in gasifier ash
m_{bf}:	biomass mass annually used in plant [t]
c_{transp}:	cost of transport to landfill [€/t]
c_{disp}:	cost of disposal to landfill [€/t]

3.2.2 Energy requirement of the conversion stage

A direct non-renewable energy requirement contribution to the conversion stage results from fossil fuel consumed during plant start-up. The annual energy requirement can be estimated from the plant thermal capacity and the start-up time.

A significant energy input to the conversion stage results from the construction of the conversion plant. The energy input is calculated based on an energy requirement of 1050×10^6 MJ provided for the manufacture and installation of a 20 MW_e biomass plant (Grant et al., 1995).

3.2.3 Environmental emissions from the conversion stage

Point source emissions in the form of flue gases are the most significant contribution to atmospheric emissions from the conversion stage and the only ones considered. Specific air emissions from the conversion stage can be estimated based on the fuel elemental composition, the efficiency of the product gas and flue gas cleaning equipment, and equipment requirements (i.e. gas quality requirements of the gas turbine). Emissions such as fuel bound NO_x, SO_2, CO_2, and PM can be estimated based on biomass composition and assumptions on the efficiency of the gas cleaning equipment and on the gas requirements of the energy generating equipment. Emissions such as thermal NO_x, CO and NMHC require knowledge on the combustion characteristics of the generating equipment. They are related to combustion equipment performance and to the use and efficiency of end-of-pipe technologies employed for their reduction (e.g. selective catalytic reduction (SCR)). Emissions are also estimated based on measurements by plant operators. Table 79 and Table 80 provide air emissions for the ARBRE and Värnamo plants.

Table 79: Specific emissions from the LP-BIG/CC ARBRE plant (Source: Cannon, 1997; Ståhl, 1997 and CEC, 1995)

Pollutant	**Emission**					
	mg/Nm^3(flue gas)			**mg/MJ(biomass)**		
	Min.	*Max.*	*Mid-range*	*Min.*	*Max.*	*Mid-range*
NO_x	20.5	51.3	35.9	14.1	35.4	24.8
CO	62.5	125	93.8	43.1	86.2	64.7
CH_4	0	0	0	0.0	0.0	0.0
CO_2	114690	114690	114690	79096.6	79096.6	79096.6
PM	2	2	2	1.4	1.4	1.4
SO_2	1.6	4.8	3.2	1.1	3.3	2.2
NMHC	0	0	0	0.0	0.0	0.0
N_2O	0.3	0.3	0.3	0.2	0.2	0.2

N_2O: CEC (1995) value for IGCC coal

Table 80: Specific emissions from the HP-BIG/GTCC Varnamo plant (Source: Cannon, 1997; Ståhl, 1997 and CEC, 1995)

Pollutant	Emission					
	mg/Nm^3(flue gas)			mg/MJ(biomass)		
	Min.	*Max.*	*Mid-range*	*Min.*	*Max.*	*Mid-range*
NO_x	20.5	256.6	138.6	14.1	177.0	95.6
CO	62.5	125	93.8	43.1	86.2	64.7
CH_4	0	0	0.0	0.0	0.0	0.0
CO_2	114688	114688	114688.0	79095.2	79095.2	79095.2
PM	2	2	2.0	1.4	1.4	1.4
SO_2	14.3	28.6	21.5	9.9	19.7	14.8
NMHC	0	0	0.0	0.0	0.0	0.0
N_2O	0.3	0.3	0.3	0.2	0.2	0.2

N_2O: CEC (1995) value for IGCC coal

In the case of both plants, the lowest value for NO_x emissions corresponds to the thermal NO_x component, which depends on the combustion temperature and the combustion characteristics within the gas turbine. Thermal NOx emissions are thus equipment dependent and are generally specified by the gas turbine manufacturer. The high NO_x emission value in the case of the high-pressure plant is the maximum value measured at the Varnamo plant. CO and SO_2 emissions are based on values measured at the Varnamo plant. SO_2 emissions for the ARBRE plant are estimated at 10% of the emissions of the Varnamo plant because of wet gas scrubbing. Particulate emissions are assumed to be the same in both plants and are derived from measurements at the Varnamo plant. We have then assumed that the hot gas filter and wet gas scrubber remove particulates from the product gas with the same efficiency. CO_2 emissions have been estimated based on the assumption that wood chips consist of 50% C by weight.

The emissions from a system fuelled with sugarcane residues are assumed to be the same as those in Table 79 and Table 80 for all pollutants except SO_2. SO_2 emissions for sugarcane residues are calculated based on the bagasse and harvest residues fuel mix, and on a 0.01% sulphur content of bagasse and a 0.2% sulphur content of harvest residues. For a low-pressure system with 90% efficient wet gas scrubbing emissions are estimated at 0.98mg/Nm^3(flue gas) equivalent to 0.68mg/MJ(biomass), and for a high-pressure system they are estimated at 9.8mg/Nm^3(flue gas) equivalent to 6.8mg/MJ(biomass).

3.3 Data relevant to waste transport and disposal/recycling

Only solid waste in the form of ash resulting from the conversion stage is considered. The ash consists of two components, fly ash and bottom ash, and can be disposed of to landfill or returned to the land to recycle valuable nutrients.

The specific transportation costs are the same as those shown in Table 68. Landfill costs across the European Union are assumed to range between €10 and 40/t. The biomass considered is not likely to lead to special or hazardous waste thus keeping the disposal costs relatively low (lower cost figure most likely).

The cost of stabilising and crushing ash is based on Swedish conditions and is estimated to be about €10-20/t (Nilsson, 1996). The cost of ash transportation per unit weight is assumed to be the same as that for biomass and the cost for spreading ash on land is assumed to be between €8-19/t (Nilsson, 1996) under Swedish conditions. In the case of Brazil ash is assumed to be recycled to the sugarcane fields, however, the recycling activity is not considered as it is assumed to be part of the sugarcane production cycle and not the fuel cycle in question. This assumption is likely to have very little effect on the results of the fuel cycle study.

The atmospheric emissions from ash transportation are a result of road transport by truck and can be estimated from Table 72. No other emissions are assumed to originate from ash disposal or recycling.

3.4 Data relevant to reference fuel cycles

Data has been included on coal and gas as reference fossil fuel cycles and on combustion-based biomass fuel cycles. The electrical efficiency of a modern coal pulverised fuel plant is estimated at 34% and that of a natural gas fuelled CCGT at 46%. The total co-generation efficiency of a coal fuelled CFB combustion plant is estimated at 90%, with an electrical efficiency of 28%. The biomass production and transport stages for the biomass combustion plant are considered to be the same as those for the gasification-based fuel cycle.

3.4.1 Generation costs

The generation costs of coal and natural gas fuel cycles will be of interest for comparison with the generation costs of biomass integrated gasification combined cycles. For the Swedish case study the cost of co-generation from coal has been estimated based on an investment cost of €2180/kW, a fixed annual operating cost of €69/kW, a coal cost of €1.59/GJ and a lifetime of 20 years (Jörgensen et al., 1998). For the UK case study, the cost of electricity generation from coal has been estimated based on an investment cost of €965/kW, a fixed annual operating cost of €31/kW, a coal cost of €1.80/GJ and a lifetime of 20 years (ETSU, 1994a). The cost of electricity generation from natural gas has been estimated based on an investment cost of €422/kW, a fixed annual operating cost of €18/kW, a gas cost of €2.15/GJ and a lifetime of 20 years (ETSU, 1994a). The costs of gasification-based generation are also discussed in relation to average national electricity and heat prices. In the case of Brazil, the cost of gasification-based biomass electricity is compared to estimates of marginal costs of electricity generation found in the literature.

3.4.2 Labour requirements

Labour requirements for fossil fuel cycles are estimated based on values provided for the provision of coal (925 jobs/Mtoe) and natural gas (428 jobs/Mtoe) and on the labour requirement of the Nässjö coal combustion plant in Sweden.

3.4.3 Energy requirements

The energy requirement associated with the extraction, processing and transport of fossil fuels can be estimated from Gover et al. (1996) (Table 81).

Table 81: Fossil fuel energy requirement for extraction, processing and transport

Energy use for fossil fuel extraction, refining and distribution [MJ/GJ]				
Crude oil	*Natural gas*	*Coal*	*Diesel*	*Petrol*
160	80	90	121.7	168.8

The direct energy requirement of the conversion stage consists of the fuel input to the plant and the energy necessary for the construction of the plant (the latter is assumed to be the same as that for a biomass plant).

3.4.4 Atmospheric emissions

Atmospheric emissions associated with the extraction, processing and transport of fossil fuels are provided in Table 82.

Table 82: Atmospheric emissions from extraction, processing and transport of fossil fuels (Source: Gover et al., 1996 and CEC, 1995)

Fuel	Emissions from fossil fuel production [g/GJ$_e$*]						
	CO_2	*NO_x*	*CO*	*CH_4*	*NMHC*	*SO_2*	*PM*
Coal	700	7.6	3.3	1004	2.1	0.1	9.3
Natural gas	2700	8	2.7	69.5	3.3	4.7	0

* assumed electric efficiencies to consumer: coal: 0.33; gas: 0.42 (HHV)

Emissions associated with flue gas from conversion plants are provided for pulverised coal combustion, CFB coal combustion, natural gas CCGT and biomass combustion (Table 83 to Table 86).

Table 83: Atmospheric emissions from pulverised coal combustion in the UK (Source: ETSU, 1994a; CEC, 1995 and Gover et al., 1996)

Pollutant	Emission [mg/MJ(fuel)]	
	Modern UK coal combustion	*Typical UK coal combustion*
NO_x	221.0	427.2
CO	12.2	12.2
CH_4	0.3	0.56
CO_2	88500	88500
PM	17.0	32.6
SO_2	100.9	1008.8
NMHC	6.0	6.0
N_2O	1.7	1.7

Table 84: Atmospheric emissions from CFB coal combustion (Source: Jörgensen et al., 1998)

Pollutant	Emission [mg/MJ(fuel)]
NO_x	59
CO	50
CH_4	0.3
CO_2	95800
PM	2
SO_2	167
NMHC	14
N_2O	1.7

Table 85: Atmospheric emissions from natural gas CCGT plant (Source: ETSU, 1994a and CEC, 1995)

Pollutant	Emission [mg/MJ(fuel)]
NO_x	100.6
CO	49
CH_4	17.1
CO_2	50200
PM	0
SO_2	0.7
NMHC	1.6
N_2O	1.4

Table 86: Atmospheric emissions range from biomass combustion plants (Source: van den Broek et al., 1996)

Pollutant	Emission [mg/MJ(fuel)]
NO_x	25 – 129
CO	6.5 – 215
CH_4	5 – 8.6
CO_2	100000
PM	4 – 10
SO_2	1.3
NMHC	2
N_2O	10

The emission values are also available in mg/Nm^3(flue gas). The quantity of emissions per unit of flue gas volume is needed to perform the atmospheric dispersion modelling.

4 The model

The spreadsheet model developed allows to calculate the costs, labour requirement, emissions and energy balance for the biomass and reference fuel cycles based on the data provided and the definition of a scenario. Details of how the calculations are performed are discussed in the relevant chapters. The model developed is modular and has a high degree of flexibility, and scenarios can be defined to perform calculations based on different biomass fuels and conversion plant capacity.